550.6133

BULLETIN
OF
The Geological Society of America

VOLUME 59 NUMBER

March 1948

PUBLISHED MONTHLY BY THE SOCIETY

THE JOHN CRERAR LIBRARY APR 13 1948

COUNCIL • 1948

President

JAMES GILLULY, Los Angeles, Calif.

Past President

A. I. LEVORSEN, Stanford University, Calif.

Vice-Presidents

CHESTER R. LONGWELL
New Haven, Conn.

KIRK BRYAN
Cambridge, Mass.

RAYMOND C. MOORE
Lawrence, Kans.

MARTIN J. BUERGER
Cambridge, Mass.

Secretary

H. R. ALDRICH, 419 West 117 Street, New York 27, N. Y.

Treasurer

WILLIAM O. HOTCHKISS, 419 West 117 Street, New York 27, N. Y.

Councilors

(Term expires 1948)

T. S. LOVERING
Tucson, Ariz.

C. W. KNIGHT
Toronto, Canada

MAURICE EWING
New York, N. Y.

(Term expires 1949)

CHARLES A. ANDERSON
Prescott, Ariz.

ERNST CLOOS
Baltimore, Md.

M. KING HUBBERT
Houston, Texas

(Term expires 1950)

GEORGE M. FOWLER
Joplin, Mo.

F. J. PETTIJOHN
Chicago, Ill.

EARL INGERSON
Washington, D. C.

COMMITTEE ON PUBLICATIONS

GLENN L. JEPSEN, *Chairman*

H. R. ALDRICH
(*ex officio*)

P. B. KING

A. S. WARTHIN, JR.

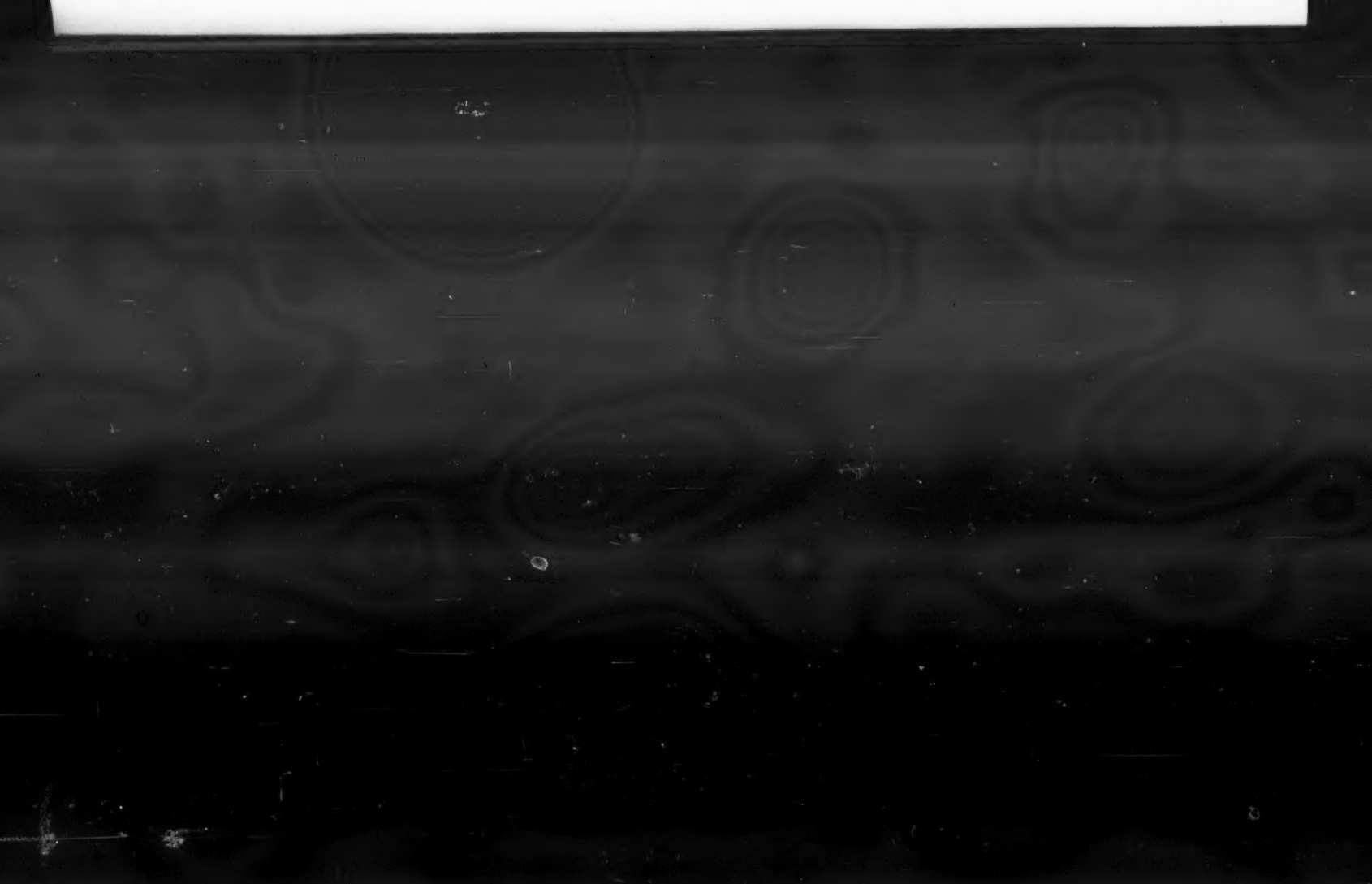
BOARD OF EDITORS

H. R. ALDRICH, *Editor-in-Chief*
AGNES CREAGH, *Managing Editor*

C. C. ALBRITTON
ROBERT BALK
R. H. BECKWITH
J. E. CUSHMAN

CORDELL DURRELL
D. J. FISHER
C. L. GAZIN
R. W. IMLAY

R. H. JAHNS
W. C. PUTNAM
H. C. STETSON
E. H. WISSER



Bulletin
of
The Geological Society of America

VOLUME 59 March 1948 NUMBER 3

CONTENTS

PAGES

Some further implications of the doctrine of isostasy. By A. C. Lawson.... 197–210

Geology and geography of central Kane County, Utah. By Herbert E. Gregory 211–248

Paleography of South America. By L. G. Weeks..... 249–282

Subscription $10 per year.

Publication Office: Mt. Royal and Guilford Aves., Baltimore 2, Md.

Communications for publication should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117th Street, New York 27, N. Y.

NOTICE.—Four weeks notice of change of address is necessary. In accordance with the rules established by the Council, claims for non-receipt of the preceding number of the Bulletin must be sent to the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter in the Post-Office at Baltimore, Md., under the Act of Congress of July 16, 1894.

Accepted for mailing at special rate of postage provided for in Section 1108 Act of October 3, 1917, authorized on July 8, 1918.

PAPERS IN PRESS FOR FORTHCOMING ISSUES

GEOLOGY OF THE TECOPA AREA, SOUTHEASTERN CALIFORNIA. By John Mason
This paper is accompanied by a colored geologic map of the area. Separate copies of the map, unfolded and in tubes, may be secured. Price 25 cents apiece. Orders should be accompanied by remittance.

STRATIGRAPHICAL PALEONTOLOGY. By Raymond C. Moore

OUR PETROLEUM RESOURCES. By A. I. Levorsen

PUSHING BACK THE HISTORY OF LAND MAMMALS IN WESTERN NORTH AMERICA. By Chester Stock

GEOMORPHOLOGY OF THE VALLEY OF THE LITTLE COLORADO RIVER, ARIZONA. By Orlo E. Childs

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 59, PP. 197-210 MARCH 1948

SOME FURTHER IMPLICATIONS OF THE DOCTRINE OF ISOSTASY

BY ANDREW C. LAWSON

Isostasy, as a fundamental principle of geology which explains the uplift and support of mountains, was discovered by Airy, named by Dutton, and rationalized by Barrell. Until the appearance of Barrell's papers (1914–1915) on the strength of the earth's crust it had been logically impossible to accept or to apply the doctrine propounded by Airy. Geologists, familiar as they were with the structure of mountains, were ready enough to believe that orogenesis involved downthrust as well as uplift, but the sinking of the root of a great range into heavier rock, to secure support by flotation, implies a disposal of the heavier rock displaced. How is the displaced rock disposed of? No one was able to answer that question. Geological opinion was committed to the view that the rocks of the lithosphere become increasingly stronger with depth. Even at the surface the essential material of the earth's crust, upon which the veneer of sedimentary strata rests, is very hard and strong. Samples of these exposures of the lithosphere may of course be crushed, and their strength is measured by engineers in terms of the compressive stress adequate to crack small unconfined prisms. But that these rocks, greatly strengthened in depth, should flow away before a descending mountain root was incredible. That solid crystalline rocks actually do flow was well known to students of Archean terranes; but to them this was a local phenomenon, incident to mountain-making movements. The recorded observations appear to have had but little effect in preparing geologists for the recognition of solid-rock flowage on a grand scale.

As to plastic yielding in front of descending mountain roots, the difficulty was not only the strength of the rocks and their resistance to the transportation by flowage; there was no accommodating space into which such flowage could proceed. Thus, while geologists were willing to concede that there must be an enormous downward mass movement induced by the load, due to tangential compression of a mountain belt, yet they balked at the notion of downthrust without provision for the accommodation of the rocks displaced by the descending root. That accommodation in the case of a large mountain range measures millions of cubic miles. Considerations like these greatly hindered the acceptance of the doctrine of isostasy in the 25 years between the utterances of Dutton and Barrell. They were based on the notion of increasing strength and rigidity of rocks with depth.

But while geologists had thus come to a logical *impasse* in their attempts to evaluate isostasy as a doctrine which concerned them greatly, geodesists proceeded, with vigor and sustained industry, to explore and measure gravitative stress in the lithosphere. By measuring the force of gravity at many localities they found that departures from the ideal figures, which a completely balanced earth should yield, were almost universal but generally quite small.

These departures from the ideal or calculated force of gravity were called "gravity anomalies" and were considered to be so slight as to present no obstacle to the acceptance of isostasy as a general principle governing the configuration of the surface of the earth. Indeed, geodesists appeared to be much more thoroughly satisfied with the reality of isostasy than were geologists. A matter of grave concern in these geodetic investigations was the depth of the level of compensation—that is, the level below which stress difference, temporary or enduring, due to the load on or in the earth's crust, fades out. But there has been little unanimity as to this depth of compensation, and its measure has varied from time to time even in the pronouncements of the same investigators. In general, and in the course of years, that depth has been adopted for the level of compensation which tended most to reduce the size of the gravity anomalies.

It has been characteristic of the geodetic inquiry into the validity of isostasy that it has had to do, in all of its prolonged phases, with static conditions. The loads, whether positive or negative, the support of which it seeks to explain, are chiefly the immobile inequalities of the relief of the earth's surface. It has never looked into the effects of those shifts of load which are of paramount interest to geologists. The immediate, or dynamic, effect of the growth and waning of continental ice sheets, the growth of large deltas, the uplift of mountain ranges and their reduction to peneplains, as well as the rise and fall of sea level are conspicuously absent from most of the geodetic discussions of the mechanism of isostasy. Mountain ranges are represented as flat-bottomed, as if downthrust of their lower parts were taboo. While flotation is not denied as the means of support of the salient features of the relief of the earth's surface, the immersion of the float in the sustaining medium of heavy rock is not recognized as an essential feature of the mechanism. It is not my purpose, nor my desire, to minimize the great and enduring value of geodesy for geological science. We cannot blame geodesists for their shortcoming. They are not, and do not profess to be, geologists; and quite naturally they have not caught the geological point of view with regard to the mobility of the earth's crust. By giving us measures of gravitative stress throughout a large part of the earth's crust, and thereby establishing the validity of a doctrine of isostasy, geodesy has made an immense contribution to earth science. Geology is deeply in its debt.

But up to 1914–1915, when Barrell's papers appeared, neither geodesy nor geology could explain the operation of the isostatic mechanism. Most of the great truths of science have to pass through a hypothetical stage during which they are tested and checked before general acceptance. The conception of the asthenosphere is still a hypothesis. Barrell claimed no more for it. He presented a most admirable argument to show that, as he described it, the asthenosphere was consistent with the known physics of the earth's crust. Other than this his chief argument was that, without the asthenosphere, there could be no such thing as isostasy. He was firmly convinced, on the basis of the geodetic findings as to the distribution of the stress of gravity, that isostasy is a true principle operating through an adequate mechanism.

The existence of the asthenosphere is a useful hypothesis in that it not only rationalizes the principle of isostasy by supplying a feasible mechanism for its operation, but it stimulates geological thinking and enables us to expand the principle, in specu-

lation at least, along the lines of its far-reaching implications. No one can successfully engage in scientific speculation, which is the mother of discovery, if his reasoning be based on some assertion which, he suspects, cannot be true. And just that was the stumbling block that tripped up geology before Barrell removed it by his hypothesis of the asthenosphere. Clear thinking as to the flotation of mountains was not possible until that brilliant idea provided the avenue of escape for the rock displaced by the depression of their roots.

In my paper on the Mississippi delta (Lawson, 1942) I left the embankment, with a thickness 12 km. out as far as the present shore line, lying in isostatic equilibrium in a flat-bottomed sag of the sea floor upon which it had been deposited. The level bottom of the sag flows from the assumption which I made, for convenience in discussion, of a uniform initial depth of water of 4 km. at the beginning of the deltaic cycle. I intimated that the delta was, in the geological sense, approaching the critical stage of its development, at which it would suffer collapse by horizontal compression in the earth's crust. The predicted collapse, it was suggested, would initiate the uplift of a great mountain range.

In the present paper I assume the validity of the doctrine of isostasy and proceed to discuss some of the consequences which flow from that assumption. My discussion is by no means comprehensive or exhaustive, but a few of the results are, or should be, of interest to geologists; and I present them as deductions, without attempting rigorous proof of their truth. In some previous papers, accepting Barrell's position in depth for his asthenosphere, I have thought that the mobile rock of the lithosphere, which is displaced by the descending roots of mountains, was the dunite of density 3.3. Today, I am of the opinion that the asthenosphere comprises the basalt which must first be displaced by the descending root of a growing mountain before the dunite is reached. The justification for this change in view will appear later in this paper.

I shall begin my remarks by pointing out how sea level is affected by shift of load under the control of isostatic balance, as an illustration of the mechanism at work in the lithosphere when that balance is disturbed.

Mean sea level at any point on the coast is usually regarded as constant. Engineers, concerned with the relative levels of structures above or below the surface of the earth, reckon from local sea level as zero. Astronomers have a constant figure for the mean distance of the surface of the sea from the center of the earth. Navigators have great confidence in the constancy of the relative positions of sea and land in all parts of the world, although aware, of course, that the local depth of water may vary by reason of changes on the sea floor.

This firm belief in a constant hypsometric relation of sea and land seems to be justified by the modern practice of persistent reading of gauges, and comparing the results with benchmarks on land. Notwithstanding the well-recognized fact that, in the Mediterranean, temples and other structures have been partially submerged and have again emerged, these modern gauge readings have not, insofar as I am aware, revealed any noteworthy vertical shifts of the relation of land and sea.

But, going back of the date of Greek temples, geology has established the fact of such shifts, wide in extent and large in vertical measure. We are now living in what

remains of the Glacial period. Coleman, in his book on ice ages, has estimated that the continental ice sheets of our time are still half as extensive as they were at their maximum. The Glacial period comprises a four-fold alternation of maxima and minima of ice. Since the ice of continental glaciation was of course derived from the ocean, the development of every maximum caused a lowering of sea level and of every minimum a rise. But the measure of the fall of the surface of the sea with reference to the center of the earth was not so great as that of the layer of water transferred to the continents in the form of ice. The transfer involved a shift of load from the entire extent of the ocean to a fraction of the continental area. According to the doctrine of isostasy, shift of load from one region to another is compensated by a counter flow of rock mass in depth to maintain balance (Lawson, 1924). The balance is of mass but not of volume, and, since the density of the rock flowing in depth from the glaciated continents back to the suboceanic region, to compensate for loss of water, is three times that of water, the rise of the sea bottom by compensation, and therefore of the sea surface, is only about one third of the thickness of the water removed by evaporation. The lowering of the sea level, in reference to the center of the earth, is thus only two thirds of the thickness of the water removed.

The surface upon which the continental ice sheets lay was lowered by the thickness of rock of density 3.05, which was transferred to the oceanic region, and the mean altitude of the glaciated area was increased by the thickness of the ice less that of the heavy rock removed in depth. There have been several glaciations in geological time long antecedent to the Glacial period, and as many falls and rises of sea level. Every one of these has had an important effect upon the configuration of the continents, since every one has meant a vertical shift of the base level of erosion. When the sea level drops relatively to the continents, streams cut their canyons deeper in the coastal mountains, and the shore moves seaward. When it rises, the sea encroaches on the valleys the river currents are checked at the new sea level. Their load of gravel, sand, and silt is dropped in a succession of thin layers to build up gently sloping or flat valley floors.

The effect of the fall and rise of sea level due, certainly in part, to glaciation and deglaciation may be realized by a consideration of the physiography of the coastal region of middle California. At the Golden Gate, almost immediately under the great bridge, soundings have shown the existence of a sharp V-shaped gorge, cut in rock. The deepest water found in this channel by the U. S. Coast and Geodetic Survey is 382 feet. But this may not be the maximum which has been stated by others, without the authority of the Coast Survey, to be 414 feet. Since exactitude of figures is not essential to this discussion, I may continue the latter with a depth of D feet for the middle of the gorge. This feature of the sea bottom is taken to be a drowned river gorge at the outlet of the drainage of middle California, cut when the sea level was somewhat lower than $-D$ feet. It may be dated hypothetically at the maximum glaciation of the Glacial period, when the sea level was at its lowest for that period.

Since then the area of the continental ice sheets has been reduced to half their maximum extent, and the thickness of the residue has been diminished. Probably the residual continental ice sheets of our day are not more than half as thick as they

were at the time of maximum glaciation. The volume of the ice remaining is, from this estimate, about one quarter of the accumulation at its maximum. Considerations entering into the estimate are: (1) the amelioration of climate indicated by deglaciation, (2) the consequent change of the gradient of the glaciers, (3) the isostatic rise of the continental surface upon which the ice rests, by reason of reduction of thickness by melting. It thus appears probable that, since the maximum of glaciation, three quarters of the ice then piled up on the continental surfaces has been restored to the ocean. Since that maximum the sea level has risen $D+$ feet relatively to the adjoining surface of the California coast. The plus sign in the figure comes from the fact that sea level at its lowest was somewhat lower than the bottom of the gorge under the Golden Gate Bridge when it was functional as a stream trench.

That some large fraction of this rise of sea level was due to the melting of the continental ice sheets goes without saying. How large that fraction may be is a question that requires further discussion. When we consider the problem it is necessary to discriminate between the movement which is due to a change in the volume of the ocean and that which is merely relative to a vertically mobile coast. Such mobility is characteristic of the coast of California. A notable instance of this, on a large scale is to be found in the insular portion of the coast of southern California, as described and illustrated in my paper of 1893. Here, under the same general geological and climatic conditions, are three insular masses: San Pedro Hill, altitude 1475 feet, Santa Catalina Island, altitude 2109 feet, and San Clemente Island, altitude 1964 feet, arranged in a nearly north-south line, 60 miles long, and about equally spaced. San Pedro at the north and San Clemente at the south have emerged from the sea, as proved by magnificent wave-cut terraces, while Santa Catalina has been depressed. The latter evidently lies in the axis of a syncline, formed in our day, while San Pedro Hill and San Clemente are anticlinal uplifts. During the progress of this orogenic movement, an observer on San Clemente or San Pedro Hill might have confidently asserted that the sea level was falling, while another on Santa Catalina might have been equally convinced that the same surface was rising. If the development of this great syncline had been proceeding during the Glacial period, as it most probably was, the relative vertical displacement due to that cause would have been complicated by real rises and falls of sea level corresponding to the minima and maxima of continental ice in the succession of glacial epochs.

From the foregoing discussion, based on observations along the Californian coast, it will be apparent that, when we talk of the rise and fall of sea level and, particularly, when we profess to estimate the measure of such rise or fall, we must be precise in our language.

Returning now to the Golden Gate, it may be asserted without question that there has been a great change in the ***relative*** vertical positions of sea and land. Whatever the cause of that change, we may be sure that there are two aspects of the problem, one concerned with relative displacements due to deformation of the earth's crust and another with absolute displacements due to the removal of water from the ocean and its restoration in due time.

Both north and south of the outlet at the Golden Gate there are many valleys tributary to it, besides the Great Valley and the streams draining into it from the

Sierra Nevada. At the time of maximum glaciation, when the aggregate drainage of the region flowed through to the rocky trench at the Golden Gate, D feet below present sea level, the valleys of the Coast Ranges were rocky gorges. The streams had not reached the base level of erosion, and alluviated bottoms were not features of the physiography. With the relative uplift of sea level from $D+$ to 0, all of these gorges and the Great Valley itself were progressively alluviated and so acquired their present broad, very gently sloping valley floors.

Although I have recognized that there may be other causes than the simple one of deglaciation and the restoration of water to the oceanic basin to account for the rise of sea from $D+$ to 0, I may now say that there is one other cause no less certain than that of the melting of continental glaciers. The water restored to the ocean by deglaciation was a load removed from the glaciated parts of the continents and placed upon the sea floor. This shift of load necessitated inevitably isostatic adjustments. The continents relieved of their load of ice rose, and the oceanic region sank as the shift proceeded. The relief of load on the continents was partial and irregularly distributed. The load added to the sea floor was the same everywhere, but very much less, per unit of area, than that removed from the glaciated parts of the continents. The area of glaciation at its maximum was about one fifteenth that of the ocean.

By tentatively assuming that the rise of sea level, as measured at the Golden Gate —*i.e.*, $D+$ feet—is 414 feet, and is due wholly to deglaciation and its consequent isostatic adjustments, we may obtain a figure for the mean thickness of the continental ice at its maximum. Let x be this figure. Then $.75x$ has melted and gone to the ocean, leaving a mean thickness of ice $.25x$ over the area of maximum glaciation. Ice has a density of .9, and its relative load per unit of area as removed by melting was $.75x \times .9 = .675x$. This load distributed to the ocean as fresh water was $\frac{.675x}{15}$ or $.045x$ p.u.a. Its thickness was also $.045x$ feet. This is effectively the same as a load of heavy rock (basalt of density 3.05) transferred back in depth from the oceanic column to the glaciated area for isostatic compensation. The thickness of the basalt which thus flowed out from under the ocean was $\frac{.045x}{3.05}$ or $.015x$. This last figure is then the measure of the drop of the sea floor, and the fall of sea level.

At the Golden Gate the present depth of water—*i.e.*, the measure of the relative rise of sea level—assumed to be 414+ feet, is made up of $.015x$ due to drop of sea floor plus the thickness of the layer of fresh water from the melting continental ice sheets, about $.045x$. Thus

$$.015x + .045x = 414 \text{ feet}$$

and

$$x = 6900 \text{ feet}$$

The figure thus arrived at for the mean thickness of the ice at its maximum extent may be compared with those for the glaciation of North America on the basis of data recorded by Coleman. These are: Cordilleran glacier 8000 feet−, Keewatin glacier 7300 feet+, Labradorean glacier 5000 feet+. The mean of these is 6760 feet. But

Coleman's figures are for altitudes above present sea level and do not make adequate allowance for the isostatic depression of the continental surfaces by the load of ice. His figures apply also to maximum values for the thickness of the ice, while the 6900 feet here deduced is for the mean thickness of the ice at maximum glaciation, on the assumption that the only causes in rise of sea level at the Golden Gate, are deglaciation and its consequent isostatic adjustments. My own figures are, of course, doubtful as to the absence of local deformation, particularly in the light of the positive evidence of local deformation of the coast of Southern California, which I have presented.

Since, however, a mean thickness of 6900 feet of ice at the maximum would, by the subsequent deglaciation, fully account for the rise of sea level as measured at the Golden Gate, I am inclined to the view that no other explanation is necessary. That is to say: I regard 6900 feet as a reasonable and approximately correct figure for the mean thickness of continental glaciation at its maximum. It does not seem to matter much in which of the glacial epochs of the Glacial period that maximum occurred. If the Coast and Geodetic Survey figure of 382 feet be taken as the real depth of the gorge, then the mean thickness of ice at maximum glaciation would be 6366 feet.

Passing now to other phases of the fluctuation of sea level, with reference to the center of the earth, I call attention more particularly to the effect of continental erosion. The reduction of continental surfaces by atmospheric and river erosion involves a shift of load from the crustal columns under the land to those under the sea. The best estimate of the rate at which that shift is proceeding is that of Dole and Stabler (1909). According to this classical work the thickness of the load removed from the basin of the Mississippi is 56 mm. per 1000 years. The relative load shifted may be taken to be $2.67 \times 56 = 149.52$ per unit of area of the continental surface.

Since the area of the oceanic column is three times that of the continental column, the mean thickness of the layer of sediment delivered to the sea floor is 56/3 mm. per 1000 years; and it displaces sea water of density 1.026. The water displaced by the deposit is, however, not removed except in the case of deltas. It is merely lifted above the layer deposited and is manifest as a rise of sea level. It continues to be an effective part of the load on the oceanic column; and the added load remains $2.67 \times 56/3 = 49.84$ p.u.a. The continental column has lost a load of 149.52, and the oceanic column has gained 49.84 p.u.a. This process of loss and gain of load would throw the two columns out of balance, but this tendency as it develops is corrected by a transfer of heavy rock in depth from the oceanic to the continental column. Let x be the thickness of the layer of basalt of density 3.05 which is thus transferred per 1000 years to maintain isostatic balance. Then:

$$-149.52 + 3.05x \times 3 = -3.05x + 49.84$$

whence

$$x = 16.341 \text{ mm. p.u.a. per 1000 years}$$

The substitution of 16.341 for x in the equation shows that the two columns are in balance, when the transfer has been made, for the prevailing rate of erosion. That rate is probably about the same for all the continents, and the assumption here made for the purpose of clarifying the argument is that it is 56 mm. per 1000 years.

But it may be urged that, as the continental surfaces approach peneplanation, this

rate will be greatly reduced and will eventually become zero. This objection, however, takes no account of renewal of relief. A better assumption than inevitable peneplanation is that, since relief is a resultant of orogenesis and erosion, and always has been so, the mean altitude of the continents has departed but little from a constant figure throughout geological history, as far back as we can read it. For at least 1,500,000,000 years the record indicates a relief not essentially different from that of the present. The only approach to a world-wide peneplain that I am aware of is that developed in the interval between the last of the Archean granites and the Algonkian, represented on the American continent by the Animikie and the Keweenawan and their correlatives. If, then, the notion of constancy of mean altitude of continental relief, under the control of isostasy, is a reasonable working hypothesis, we may also tentatively accept the rate of continental erosion at the constant value of 56 mm. per 1000 years, throughout geological time.

Since the thickness of basalt withdrawn from the oceanic column to compensate for erosion of continental surfaces is 16.341 mm. per 1000 years, the same figure is the measure of the sinking of the floor of the sea in the same time. With the drop of the sea floor, sea level would also tend to fall. Counter to this tendency is the rise due to the growing deposit of erosional waste on the sea floor. The thickness of this deposit per 1000 years, considering the relative area of sea and land, is $56/3 = 18.666$ mm., and the net rise of sea level is $18.666 - 16.341 = 2.325$ mm. per 1000 years. The rise of sea level in the deltaic cycle of 55,000,000 years for the Mississippi, up to the present, is thus .128 km.[1]

The reference in the foregoing paragraphs to renewal of relief by orogenic movements leads naturally to the consideration of the effect of particular diastrophic episodes on the level of the sea. There are various types of mountains, but all of them result in one sense from horizontally compressive stress in excess of the local strength of the earth's crust. Even volcanic piles, so common the world over, owe their existence to compressive stress. The most common type of nonvolcanic mountain is that which arises out of the sea and is composed for the most part of stratified deltaic sediments. The latter usually originate in shallow water but may extend rapidly into deep water, where the sediments, displacing sea water, notably increase the local load on the sea floor. The sea floor sinks isostatically under the added load, making room for more sediments at the top of the growing embankment. The depression thus inaugurated is accommodated by an outflow in depth from beneath the delta of the relatively heavy rock of the basement. The growth of the delta is vertically down, and horizontally seaward. Its top is constant at sea level but varies with independent fluctuations of that surface.

In the discussion which follows the assumptions are: (1) that the initial depth of water was 4.2 km., (2) that the landward flow of rock in depth to compensate the erosional removal of load was chiefly basalt, (3) that the rise of sea level in a cycle of 55,000,000 years was .128 km., and (4) that the density of the deposits of the embankment is 2.4. Under these assumptions the embankment at its bottom sinks to a depth below sea level of 13+ km. into the region of strong rocks, without deforma-

[1] This figure replaces that arrived at in my paper of 1938 partly by error and partly by the assumption that the compensating rock flow from the oceanic to the continental columnar consists of dunite.

tion. At this stage the embankment collapses under the tangential compressive stress of the region into which it has sunk. The collapse is the initiation of a mountain-making movement. The weak rocks of the accumulation become intricately folded. The top of the delta is lifted above sea level, and its bottom sinks several times the amount of the uplift into the heavy rocks underlying the depression, thereby acquiring support by flotation. The deltaic cycle has ended, and orogenesis has set in. In the orogenic cycle the sinking and consequent displacement are on a much vaster scale, and at a much more rapid rate than that of the period of sedimentary accumulation. The rocks of the basaltic layer are pushed aside, and the developing root of the new mountain penetrates the very hot but solid dunite below.

In the early part of the deltaic cycle the embankment grows both upward, substituting sediments for sea water, and downward. When the upward growth is finally stabilized and stopped at the new sea level the bottom of the embankment has sunk into the sea floor much farther than the top has risen. Accommodation for the sinking is provided by the outflow of heavy rock in depth. The measure of the sinking may be found from an algebraic equation: Let x be the depression of the sea floor under the embankment in kilometers. The thickness of the latter is $.128 + 4.2 + x$ at density 2.4. Taking the thickness of the basalt at the beginning of the cycle at 37 km., this would become $37 - x$ at its close. The equation then is:

$$2.4\,(4.2 + .128 + x) + 3.05\,(37 - x) = 1.026 \times 4.2 + 2.4 \times .128 + 3.05 \times 37$$

whence $x = 8.878$ for a deltaic cycle of 55,000,000 years. The total thickness of the embankment for the new sea level just prior to the collapse is $4.2 + .128 + 8.878 = 13.206$ km.; and the total depth from the new sea level to the bottom of the basalt is $13.206 + 37 - 8.878 = 41.328$ km.

The two orogenic movements above referred to—(1) the displacement in depth to make room for the mountain root, and (2) the penetration of the root into the hot dunite—comprise crustal deformations of the first magnitude. The necessary support for the rising mountain determines the condition that the volume of the collapsed delta immersed in the heavy rocks is several times greater than that lying above the upper limit of the heavy rocks; just as the submerged fraction of a block of ice is much greater than the portion emergent from the water in which it floats.

The volume of a great mountain range say 3000 km. in length, having a mean altitude of 7+ km. above the sea floor at the origin of the delta, and a width of, say, 300 km. would be over 6,000,000 cubic kilometers. The volume of compressed and depressed deltaic sediments supporting such a range by flotation would be several times this—something like 50,000,000 cubic kilometers. This is roughly the measure of the rock displaced in depth.

If we suppose the site of the original delta embankment to have been on the sea floor, beyond the continental limits, the strong rock first displaced would consist almost wholly of basalt, the thickness of which is taken to be about 37 km. Its outflow would have a direction counter to that of the compressive stress which caused the collapse of the delta, and which could have been propagated only in the basalt. It seems thus probable that the compressive stress in the basalt is at its maximum near the top of that layer, and diminishes sufficiently in a depth short of 37 km. to

permit the outflow necessary to accommodate the descending root of the growing mountain. The level at which the outflow first becomes possible would be, from this point of view, at the depth of the bottom of the sediments (13.206 kilometers) at the moment when the collapse sets in.

The rise in temperature with increasing depth may also be presumed to mobilize the basalt.[2] It is clear that the displacement of the basalt implies a flow of the latter on a large scale. The relative diminution of compressive stress with depth, indicated by the counter outflow, and the increasing mobility of the basalt, may thus be essential features of the mechanism which uplifts mountains.

The isostatic outflow of basalt is probably chiefly landward. It would ultimately extend under the continental surface as far as required for compensation to regions of excessive erosional removal. It may be not too extravagant a suggestion to say that all the known occurrences of basalt on the continents may be derived from such isostatic migrations in depth. However that may be, a more general statement is certainly true: that erosion implies a steady transfer, throughout geological time, of rock mass of relatively low density to the ocean and a return of flow of heavier rock in depth to compensate the reduction of mass in the continents. The embarrassing thing is that, while the mass removed by erosion is fully compensated, the volume restored to the continents is notably less than the volume removed and that, therefore, by this time the continental surfaces should all be reduced to peneplains. This embarrassment is of course recognized in geological literature. The escape from it is, however, easy if we invoke an independent renewal of continental relief; and this renewal of relief throughout geological ages is well known and certain.

Among the various manifestations of crustal deformation which make for the renewal of the relief of the earth's surface, the collapse of great deltas is probably the most common. This assertion is based on the prevalence of deltaic sediments in the make-up of folded mountains. Measured sections of these strata are not rarely about 40,000 feet and are not known to exceed 43,000 feet. The mountains which thus rise out of the ocean not only renew the continental relief but also add to the expanse of the land.

To summarize: The maximum known thickness of deltaic sediments in folded mountains, about 13+ km., probably indicates the limit of subsidence of the embankment, at which the weak sediments composing it are no longer able to withstand the compressive stress normally prevailing in the upper part of the lithosphere. At this stage of depression horizontal collapse sets in. The deltaic cycle has been supplanted by an orogenic cycle, continuing the depression at a more active rate; and at the same time the surface rises. The uplift demands a root for its support by flotation. In its downward growth the root shoves aside the basalt and penetrates the underlying dunite. For a great mountain range the volume of the displaced basalt runs into many millions of cubic miles. The displacement involves a mobility comparable to that of Barrell's asthenosphere, although the outflow of the basalt is at a level far above the depth at which he places his zone of maximum weakness. Without abating

[2] The collapse of the embankment due to compressive stress would involve a sudden increase of vertical stress due to the failure of arch support; and this increase of pressure would affect the melting point. *See* Johnston and Adams (1913).

my admiration for Barrell's brilliant contribution to the doctrine of isostasy I may say that he seems to me to have located the asthenosphere at too great a depth.

In the advanced stages of orogenic deformation there would be no basalt under the site of the original delta; and this may explain the absence of basaltic eruptions in the orogeny of mountains arising from the collapse of large deltas the world over.[8] The mobility and isostatic distribution of basalt may explain the prevalence of such eruptions in regions remote from folded mountains.

It has been pointed out that the displacement of the basalt by the descending root of the growing mountain permits the latter to penetrate the deeper dunite. The consequences of this penetration are not less important in the orogenic mechanism of folded mountains than the thrusting aside of the basalt which originally lay under the site of tne delta. The large difference in the temperature of fusion of dunite and of aggregates of granitic minerals determines a condition which explains batholiths known in the cases of many folded mountains, that have been sufficiently deeply eroded. The evidence of the intrusive relation of the granite to the overlying sediments is usually abundant and unmistakable. It may be said that such central batholiths are as characteristic of the erosional residues of great folded mountians as is the absence of the basaltic intrusions in their orogenic history. There was a time in the history of geology when granites were regarded as the remains of the original crust of the earth. But from observation of granites on various continents I have been unable to discover any which are not intrusive on their margins into rocks of surface origin. My conclusion is that all granites are of secondary origin and are to be found characteristically in the cores of folded mountains. The general absence of large bodies of peridotite associated with the granitic batholiths of folded mountains the world over suggests that the greatly deformed sediments of the mountain root passed through the basalt directly into the dunite. With but few exceptions such peridotites as are known in this connection are small and may result from the fusion of occasional fragments of basalt carried down with the descending root into the hot dunite. For a mountain uplift of 7 km. and a density of 2.67 for the rocks of both the mountain and its root, the immersion of the latter, free from large masses of basalt, in the dunite would be 18.643 km., as may be readily shown by the use of an algebraic equation of balance. It thus appears that the total thickness from the summit of the mountain to the extremity of the root amounts to $7 + 4.328 + 37 + 18.643 = 66.97$ km. But the total thickness of the undeformed delta embankment when the collapse inaugurated the deformation was only 13.206 km. The vertical elongation of the column in the ratio of 1 to 5 is due to the compressive stress to which the new mountain owes its existence. This ratio harmonizes fairly well with various measurements by field geologists of the local shortening of the arc of the earth's crust by acute deformative compression of sedimentary strata. (*See* particularly Chamberlain, 1910, and Claypole, 1885.) According to these geologists the shortening of the arc by acute folding and thrusting may locally range up to a reduction of several miles to one; and this implies of course a corresponding vertical elongation.

The rise of the mountain was due to the combined effect of compressive deforma-

[8] The general absence of basaltic intrusions or extrusions in the orogenic process and the restriction of batholiths to orogenic belts is clearly stated by Kennedy in his paper on crystal layers and the origin of magmas.

tion and flotation. But flotation determines that, in large measure if not wholly, the weight of the uplifted mass does not operate to restrain the inward compressive movement, so that the latter is accelerated. Deformation of the floating mass proceeds rapidly, involving a shortening of the horizontal dimensions transverse to the axis of uplift and a corresponding elongation of the vertical dimensions. Throughout the deformative process flotation operates to keep the column in balance with all other columns, stable or unstable. Just prior to the initial collapse the embankment of the delta, with its bottom at a depth of 13+ km., lay in a trough in the basalt formed by subsidence. The walls of this trough, 8.8 km. in height, were probably the *loci* of vertical shears. The subsidence of the floor of this deep trough was accommodated by an outflow of the bottom part of the basalt, under isostatic urge engendered by the load added to the floor of the trough. That load was 13.206 km. of flat-lying sediments less the weight of 4.328 km. of water, which was in process of being displaced throughout the time of accumulation. The isostatic urge for outflow of the deeper basalt was greatly accelerated by the collapse of the embankment. The load to be kept in balance was rapidly increased by the vertical elongation of the column as well as by the uplift of mountain. The urge for outflow of the basalt, the most mobile of all rocks, became so imperative that it was eventually all disposed of and the sedimentary root of the mountain entered the dunite.

When the root of a great mountain range descends through the basalt into the dunite the latter has a temperature at which it remains solid and strong, but at which the clastic sediments of the root melt. The fusion is doubtless a long-drawn-out process, but as it proceeds the liquid rock, by active convection currents, carries the heat to higher and higher levels. There is, however, an upper limit to the process, and that limit becomes the ragged boundary between granite and the residue of the root, when freezing of the magma sets in. The boundary, as subsequently exposed by erosion, is characterized by dikes and irregular apophyses of granite, and by innumerable angular inclusions of more or less metamorphosed sediments, which have broken off from the diminishing first formed root. The melting and freezing of the root does not destroy its function as a root, which is to afford support by flotation of the new mountain range. Every batholith of a mountain range is thus functionally the root of the mountain. In the transformation from sediments to granite there are doubtless changes of density, but these are small. The changes may inaugurate an isostatic oscillation, but will not greatly affect the general outlines of the structure.

While these things are going on in depth, erosion is active at the top. The function of erosion, from the point of view of orogenesis, is that, by removal of load from the crustal column in which the mountain is situated, the vertical movement of the column is reversed. Compensation for the diminution of mass is effected by the higher flotation of the column. The granitic root slowly emerges from the heavier rocks in which it is, in its deeper part, immersed. The whole column rises, carrying, of course, the surface with it. It thus happens that the reduction of altitude of the mountain is but a small fraction of the thickness carried away by erosion. This counter action, of reduction of altitude by erosion and incease of altitude by isostatic rise, goes on throughout the entire life of the mountain. When the latter finally

disappears by peneplanation the isostatic uplift also ceases. The result is a region of great stability, such as is exemplified by the post-Archean peneplain which extends over so large a part of Canada.

Note.—Since writing the foregoing suggestions as to the genesis of batholiths I have reread the elaborate questionnaire entitled *Problems of the batholiths*, published April 22, 1933, by a committee of the Division of Geology and Geography of the National Research Council, under the chairmanship of Frank F. Grout.

This array of interrogations and comments ignores the role of isostasy in the assembling and placing of the material of which batholiths are ultimately built by a process of melting and freezing of the roots of folded mountains. It ignores the depression of the roots into solid dunite having a temperature at which they melt. It ignores the isostatic emergence of the roots, first as liquid then as solid, from the dunite, and the rise of the column, under the erosional reduction of the mountains to peneplains, thus giving us the largest exposures of batholiths where we find them. In short, it ignores the essentials of the problem of the genesis of batholiths.

REFERENCES CITED

Barrell, Joseph (1914–1915) *The strength of the earth's crust*, Jour. Geol., vol. 22; vol. 23.

Chamberlin, R. T. (1910) *The Appalachian folds of central Pennsylvania*, Jour. Geol., vol. 18, p. 228–251.

Claypole, E. W. (1885) *Pennsylvania before and after the elevation of the Appalachian Mountains; a study in dynamical geology*, Am. Nat., vol. 19, p. 257–268.

Dole, R. B., and Stabler, H. (1909) *Denudation*, U. S. Geol. Survey, W.-S. Paper 234, p. 78–93.

Johnston, John, and Adams, L. H. (1913) *Effect of high pressures on the physical and chemical behavior of solid substances*, Geol. Soc. Am., Bull., vol. 24, p. 674–675.

Kennedy, W. Q. (1938) *Crustal layers and the origin of magmas*, Bull. Vol., ser. II, Tome III, p. 24–40.

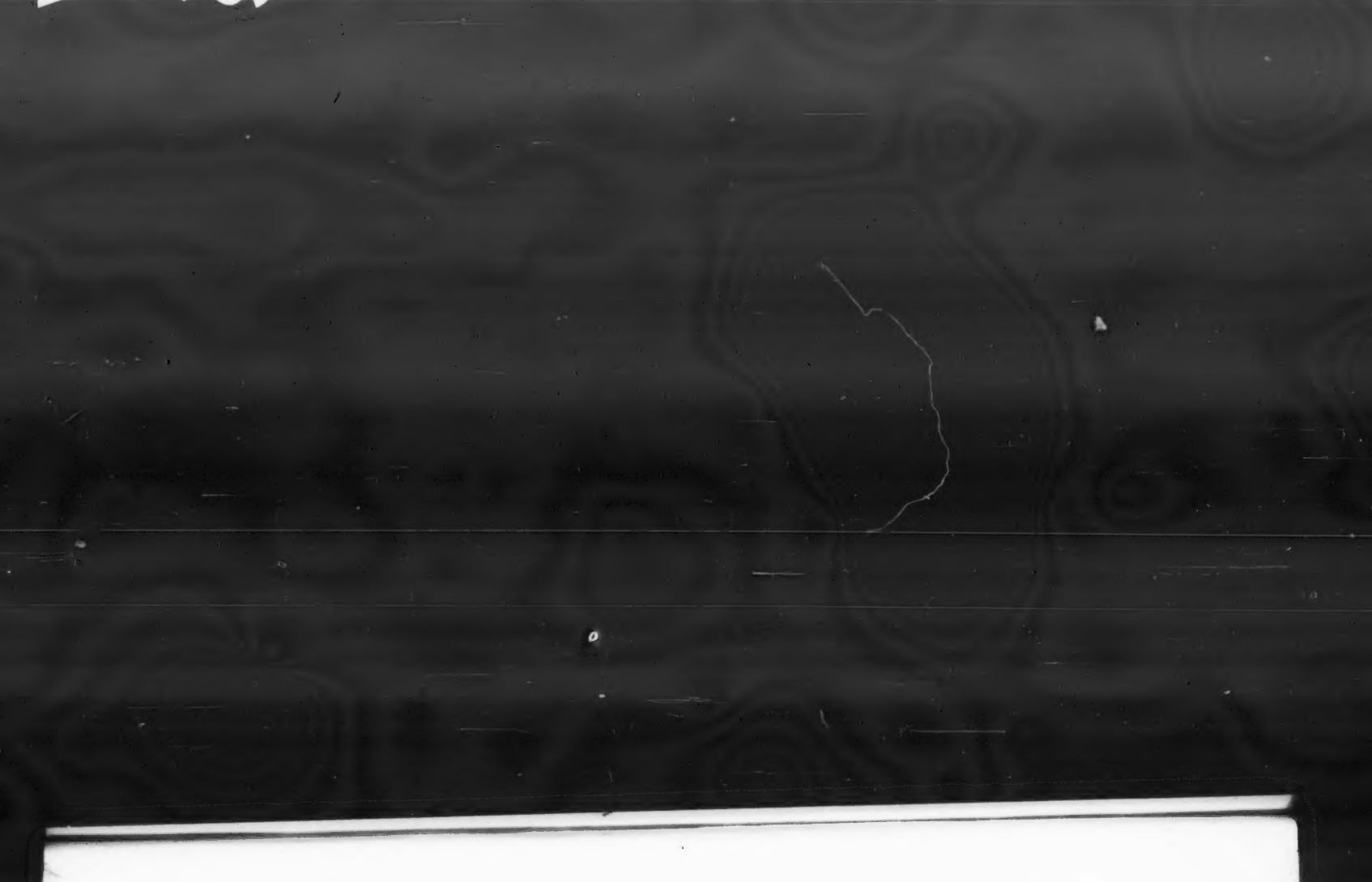
Lawson, A. C. (1893) *The Post-Pliocene diastrophism of the coast of southern California*, Univ. Calif., Bull. Dept. Geol., vol. 1, no. 4, p. 115–160.

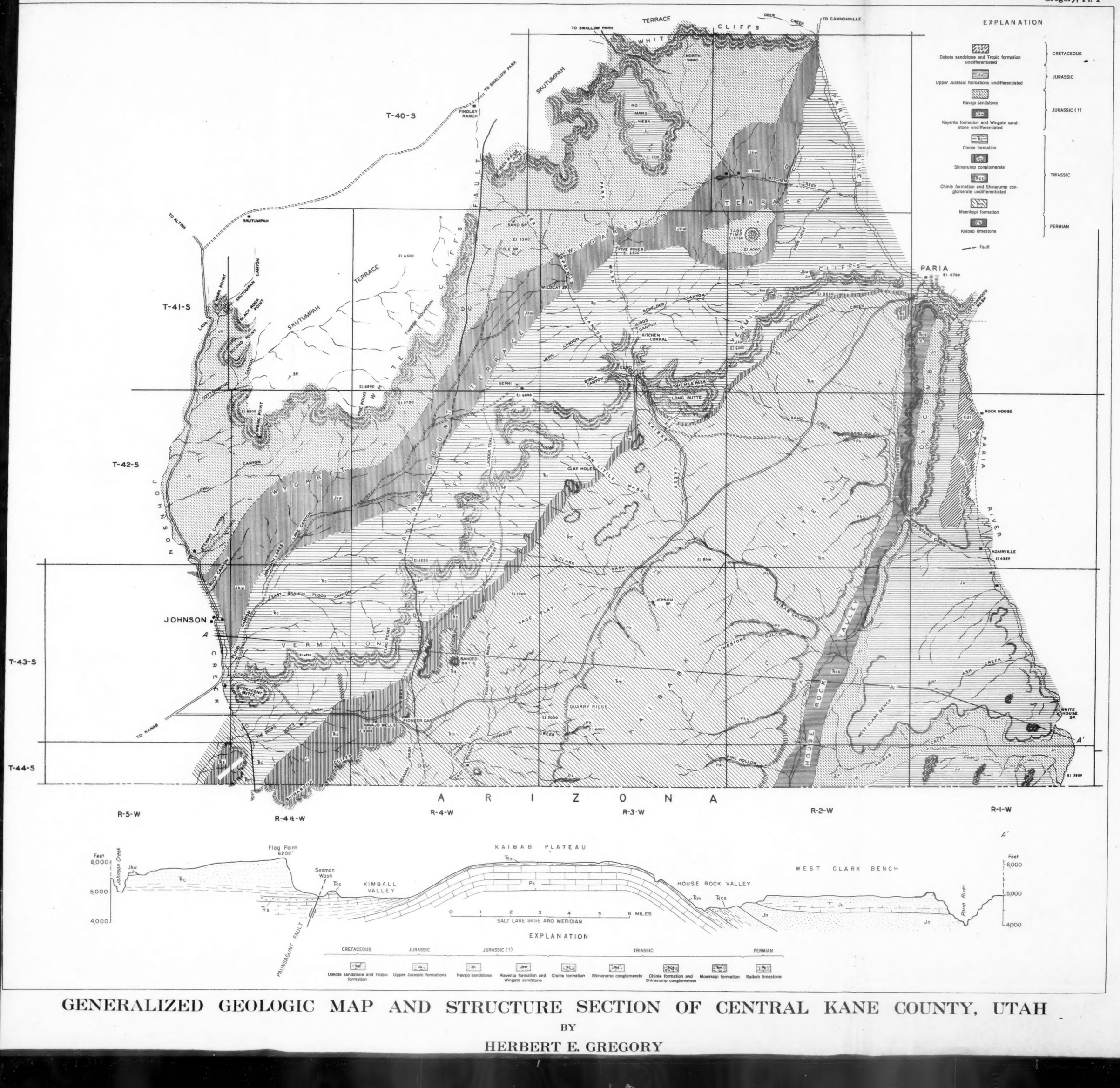
——— (1924) *The geological implications of the doctrine of isostasy*, Nat. Res. Council, Bull., vol. 8, pt. 4.

——— (1942) *Mississippi delta, a study in isostasy*, Geol. Soc. Am., Bull., vol. 53, p. 1231–1254.

Univ. California, Berkeley, Calif.

Manuscript Received by the Secretary of the Society, January 10, 1947.





GENERALIZED GEOLOGIC MAP AND STRUCTURE SECTION OF CENTRAL KANE COUNTY, UTAH

BY

HERBERT E. GREGORY

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 59, PP. 211-248, 9 PLS., 2 FIGS. MARCH 1948

GEOLOGY AND GEOGRAPHY OF CENTRAL KANE COUNTY, UTAH

BY HERBERT E. GREGORY

CONTENTS

	Page
Abstract	212
Introduction	212
Purpose and scope of investigations	212
Previous scientific work	212
Geography	213
Location, extent, and accessibility	213
Historical sketch	214
Climate and vegetation	216
Geographic features	217
Major land forms	217
Streams and valleys	219
Springs and lakes	221
Sedimentary rocks	221
General stratigraphic relations	221
Permian formations	222
General statement	222
Hermit shale and Kaibab limestone	222
Triassic formations	223
Regional relations and subdivisions	223
Moenkopi formation	225
Moenkopi-Shinarump contact	223
Shinarump conglomerate	228
Chinle formation	228
Jurassic formations	231
Subdivisions and regional relations	231
Glen Canyon group	232
Upper Jurassic formations	234
Cretaceous formations	236
Stratigraphic sections	236
Structure	240
Distribution of faults and folds	240
Paunsaugunt fault	241
Kaibab upwarp	241
East Kaibab monocline	242
Outline of physiographic history	244
References cited	247

ILLUSTRATIONS

Figure	Page
1.—Outline map of southern Utah	214
2.—Cross section, House Rock Valley	224

Plate — Facing page
1.—Map of central Kane County, Utah. . . . 211
2.—Views along Vermilion Cliffs. . . . 224
3.—Permian and Triassic rocks. . . . 225
4.—Views of Moenkopi formation. . . . 228
5.—Triassic rocks. . . . 229
6.—Wingate sandstone. . . . 232
7.—Features of Jurassic and Recent formations. . . . 233
8.—Features of East Kaibab Monocline. . . . 244
9.—Structural relations along Utah-Arizona boundary. . . . 245

ABSTRACT

This paper, based on surveys made chiefly in 1943 and 1944, describes the geography and geology of central Kane County, Utah, an area of about 570 square miles. The region is semiarid, utilized almost entirely as forage ground for sheep and cattle.

The oldest rocks exposed are the Hermit shale and the Kaibab limestone of Permian age. Above these lie the Triassic, Jurassic, and Cretaceous formations characteristic of the Colorado plateaus. Igneous and metamorphic rocks are absent. The regional north and northeast dips of the sedimentary beds have been interrupted by the broad Kaibab upwarp, the strongly accentuated East Kaibab monocline, and the Paunsaugunt fault, which have disturbed all the formations exposed. The physiographic history of the region records two long cycles of regional denudation and shorter periods of alternating aggradation and degradation. Conspicuous topographic features are the White Cliffs and their outlying mesas and peaks, the Vermilion Cliffs, the Shinarump Cliffs, the Kaibab Plateau, the Coxcomb, House Rock Valley, and two broad surfaces of erosion—Wygaret Terrace and Kimball Valley.

INTRODUCTION

PURPOSE AND SCOPE OF INVESTIGATIONS

To fill a conspicuous gap and thus provide a continuous geologic strip map across the Colorado plateau province from the Colorado boundary line westward to the Hurricane Cliffs, surveys were made in 1943 and 1944 in Kane County, Utah. Because of the short time available for field studies, and the lack of maps suitable for recording geographic and geologic observations, the work was necessarily a reconnaissance, supplemented in places thought to be critical by more complete stratigraphic lithologic, and geographic detail. However, the text and geologic map present the essentials of stratigraphy, structure, and physiography, and the newly compiled geographic base map will be of use when later work is undertaken (Pl. 1).

PREVIOUS SCIENTIFIC WORK

For the region that includes central Kane County, the geography was first described by members of the Powell and the Wheeler surveys. In 1871, on his second traverse of the Colorado canyons, Powell left the boat party at the Crossing of the Fathers and briefly examined the geographic features along his route to the village of Paria and westward along the Vermilion Cliffs to Johnson and Kanab. Wheeler (1889) states that in 1872 Lieutenant L. H. Marshall made a topographic traverse from Johnson Creek through Paria ("the last place of civilization in Utah") to the Crossing of the Fathers and recorded his observations on a hachure map. In 1872–1873

Alvin H. Thompson, Chief Geographer of the Powell Survey, located the boundary between Utah and Arizona, established base lines for latitude and longitude, and constructed the maps later published by the U. S. Geological Survey as the Kanab and Escalante sheets—the standard topographic maps for Kane and adjoining counties. In 1877 much of the flat land south of the Vermilion Cliffs was mapped by the General Land Office to give legal standing to squatter rights at Paria, Johnson City, and the larger springs.

A comparison of these maps shows marked differences in drainage pattern and in the position and extent of many land forms. Most of the township and section markers placed 65 years ago have disappeared.

The pioneer geologic investigator of the region that includes central Kane County was Howell (1875), who in 1873 traversed the canyons of Paria River and extended his studies westward along the Vermilion Cliffs, probably as far as Johnson Canyon. Howell established the sequence of the sedimentary rocks and recognized the major structural features.

The conclusions of Howell and Thompson, supplemented by a more thorough study of the Kaibab upwarp and the adjacent East Kaibab monocline (1875–1877), are incorporated in reports by Dutton (1880).

Since the publication of the comprehensive reports of the Wheeler and Powell surveys, papers on special topics relating to central Kane County have been published by Walcott (1890), Lawson (1913), and Noble (1928). The geology of the immediately adjacent regions has been treated in more recent reports (Gregory and Moore, 1931; Gregory, in press a; in press b).

GEOGRAPHY

LOCATION, EXTENT, AND ACCESSIBILITY

As defined in this paper, central Kane County lies between Johnson Creek and the Paria River and extends from the Arizona line northward to the base of the White Cliffs—approximately 570 square miles (Fig. 1). Since the once thriving settlements of Johnson City and Paria were abandoned the region has no permanent residents. Its present commercial center is Kanab (population 1397 in 1940, about 10 miles west of Johnson Creek.

In pioneer days roads passable by wagons extended from Kanab along the base of the Vermilion Cliffs to the isolated Rock House in Paria Valley and from Navajo Wells across the "Buckskin Mountain" (Kaibab Plateau) to House Rock Valley and Lees Ferry. Branch roads extended up Johnson Canyon to Skutumpah and Upper Kanab (Alton) and reached farm lands located at springs along habitable washes. During the 1880's graded roads from Park Wash and the Paria River gave easy access to the ranches in Kitchen Canyon. Most of these old roads have been abandoned.

The present road system in central Kane County consists essentially of the relocated Johnson Valley route and the recently constructed roads from Kanab to the Paria River and to the manganese mine at Long Butte. Under favorable conditions the established trail in Flood Canyon past Johnson Lakes is adapted to lightly loaded trucks, and at times of low water Paria Canyon and the Deer Springs Canyon may be

traversed by wagons and precariously by automobiles. On the lowlands south of the Vermilion Cliffs and on the Wygaret Terrace west of Deer Springs Canyon most points of geologic interest are easily reached on horseback, but in the districts about Boxelder Canyon, Tabetimp, and the Coxcomb, surveys involve the traverse of rough ridge

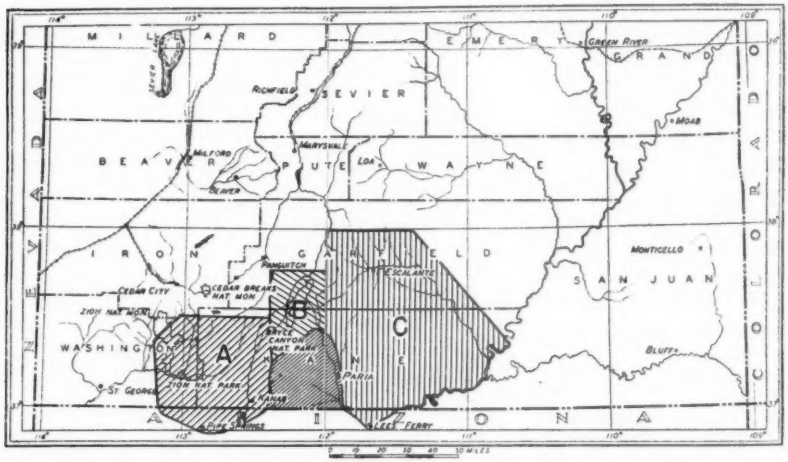


FIGURE 1.—*Outline map of southern Utah*

Showing the location of central Kane County (cross-lined) and contiguous areas from which geologic reports have been prepared. A, Zion Park region; B Pansaugunt region; C, Kaiparowits region.

tops and canyon floors, crossing vertically walled canyons, and scaling cliffs—tasks to be accomplished on foot.

HISTORICAL SKETCH

Though archeological investigations in central Kane County have been but incidental to other studies, they show clearly enough that the pioneer settlers were Basket Makers—farmers and hunters who occupied favorable sites in southern Utah as early as 2000 B. C. Cliff caves in Starlight Canyon and a few elsewhere contain well-preserved implements of wood, bone, horn, and stone, baskets, textiles of yucca and other plant fibers, and crudely made pottery characteristic of the Basket Makers. The Puebloans who followed the Basket Makers are represented by stone houses in Flood Canyon, Park Wash, and on the south slope of No Mans Mesa. In size and style of construction their buildings are inferior to those in regions immediately east and west and much inferior to the architectural masterpieces erected by their kinsmen south of the Colorado canyons. A few petroglyphs and scattered shards of pottery are believed to represent the Puebloans, and the abundant arrow points include both Basket Maker and Pueblo an types. Many of the points doubtless came from the chips and logs in the petrified forest on Fossil Wood Wash.

In the succession of aboriginal tribes in Kane County the Puebloans were followed by the Piutes. Escalante, who visited them in 1776, and the Mormons who later

took over their lands describe these early settlers as shy, peace-loving, and fairly well adjusted to their physical environment. By ingenious methods they caught mountain sheep, deer, antelope, and rabbits, porcupines, birds, lizards, and grasshoppers; they collected piñon nuts, roots, and the seeds of sunflower and other annuals, and to supplement the food obtained by hunting cultivated small irrigated fields of corn, beans, squash, and melons. The Mormon pioneers found Piutes attending their crops in Kanab, Johnson, Kitchen, and Paria valleys and along the base of the Kaibab Plateau. Though treated with kindness these seminomadic people were unable to adopt the white man's mode of life. This Kaibab clan (Kaibabits), that in 1870 numbered "several hundred", is now represented by 80 people, cared for by the Government on the Kaibab Reservation, near Mocassin, Arizona.

In a modern sense exploration of the region that includes central Kane County began with the Dominiquez-Escalante expedition of 1776 and, after a lapse of nearly a hundred years, was continued by scouts of the Church of Latter Day Saints. Escalante briefly described the country along his route south of the Vermilion Cliffs, and on the crudely drawn map accompanying his "Diary" Johnson Creek, Navajo Wells, the Kaibab Plateau, House Rock Valley, and the Paria River are recognizable.[1]

As early as 1865 the "lone hermit", Don Carlos Shurtz, established residence at Rock House in Paria Valley, and in 1869 Captain James Andrus spent several days in the vicinity of Rock House in attempts to recover livestock stolen by the Navajos. Probably in response to the encouraging reports of Shurtz and Andrus an expedition was organized at Parowan in September 1870 to investigate fully the resources of Paria Valley, its western tributaries, and the adjoining lands along the Arizona border south of Vermilion Cliffs. The exploring party included "Church officials, farmers, stockmen, lumbermen, guards, sappers, miners, etc. etc. . . . 43 souls", from Beaver, Iron, and Washington counties. Major J. W. Powell accompanied the expedition.

Soon after the report of this Paria River expedition had been published by Bishop A. Milton Musser[2] and doubtless mainly because of it, settlements were organized in Paria Valley and Johnson Valley at the most favorable places, and the villages of Rock House, Adairville, Paria, and Johnson City began their eventful history. A period of prosperity was followed by a long, futile struggle to control the erratic behavior of eroding streams. At present Paria and Johnson City are ghost agricultural towns, many outlying farms are deserted, and eastern and central Kane County have no permanent residents.

Of the 2,698,000 acres that make up Kane County, 4600 acres are classed as "irrigable," and, including dry farms, 0.25 per cent of the area was under cultivation in 1940. Profitable farming in central Kane County is restricted to lower Johnson Valley and Seeps Wash, where a few families cultivate 670 acres of irrigated and dry land during the growing season for crops, and then move out, leaving only caretakers.

From time to time buildings have been constructed and machinery installed at

[1] The long-lost map of the route of the Dominiquez-Escalante expedition, prepared by Don Bernado de Miera y Pachero in 1777, is reproduced in the Utah Historical Quarterly, vol. 9, 1941, where it is described by J. Cecil Alter and Herbert S. Auerbach.

[2] Desert News, September 21, 1870.

places which seemed favorable for the recovery of minerals of economic value. During the years 1910–1913 about 20 men were working at "the Paria gold mine", and at the same place in 1943 a group of men were attempting to mine mercury. Manganese-bearing rocks in Mine Gulch near the mouth of Park Wash have been quarried intermittently. Though this deposit contains an estimated 70,000 tons of ore with a manganese content of 10 per cent, its profitable operation is prevented by the lack of near-by water and the necessary truck haulage of 135 miles to the nearest railroad.

Experience during 75 years of occupancy has demonstrated that Kane County is a "cattle country", generally unsuitable for farming and mining. It is primarily a range for stockmen who have their homes in Kanab, Orderville, Glendale, Cannonville, and Tropic. In the words of "Jet" Johnson, who has spent his long life in developing water for agricultural and forage lands, "Cattle raising kept the people here while they were fighting for water and ever since then cattle, some sheep, Angora goats, and hogs have been the main source of income."

CLIMATE AND VEGETATION

As elsewhere in the Colorado plateau country, the climate of central Kane County is semiarid and characterized by wide annual, seasonal, monthly, and daily ranges in precipitation and temperature. The climate of the region south of the Vermilion Cliffs at altitudes of 4500 to 5500 feet is fairly well represented by records at Paria and Kanab, and field observations and the accounts of stockmen indicate that, except for a greater snow fall, a few more rainy days, less persistent winds, and somewhat lower temperatures, the climate of the areas above 6000 feet closely resembles that of the lower lands. At Paria (altitude 4700 ± feet) the records show a mean annual precipitation of 8.45 inches, a maximum of 14.09 inches, and a minimum of 4.85, and fairly even distribution throughout the year. Summer temperatures exceeding 100° are normal, but winter temperatures below zero are rare. At Kanab (altitude 4925 feet), the mean annual precipitation is 13.18—7.29 inches for the driest year and 20.70 inches for the wettiest year. The heaviest precipitation, about 40 per cent of the annual, comes in January, February, and March, and the lightest in April, May, and June. At this station the average temperature for January is 32.3; for July 74.1—the extremes are 106° and −20°, and normally the lapsed time between the last killing frost of spring and the first killing frost of fall—the growing season for crops—is 151 days; in exceptional years, less than 120.

Snow to a depth of a few inches covers the lower lands intermittently during December, January, and February; on the higher lands it may fall any time between October and March and remain in sheltered places until April or May. Representative of considerable areas, 37 inches of snow has been measured at Nephi Ranch and 22 inches at Kanab. Unlike the water from rains, most of which rushes from the surface before it can percolate into the soil, that from melting snows soaks into the ground, thus feeding springs, giving sustenance to plants, and slowly pouring water into stream channels at the time when most needed for irrigation. The best grazing lands are those that receive the most snow; most of the cattle spend the summer season on the highland back of the Vermilion Cliffs.

In central Kane County the scant and erratically distributed rainfall, the short growing season, and the dominantly siliceous soil are unfavorable for luxuriant plant growth. The cover of vegetation—everywhere patchy and over considerable areas essentially absent—is characterized by many species, each represented by a few individuals classed as representatives of the Upper Sonoran and the Transition zones. South of the Vermilion Cliffs, at altitudes of 5000 to 6000 feet, the most common plants are juniper and piñon,—the "pigmy forest"—cliff rose, gray sage, rabbit brush, black brush, Brigham tea, and numerous annuals. These plants in less abundance grow along canyons and low divides at altitudes above 6000 feet, where they are accompanied by mountain mahogany, manzanita, and Gambel oak, serviceberry, several species of grass, and a few of yellow pines. Along the Paria River and lower Kitchen Creek, cottonwoods, here and there accompanied by willows, are fairly common, and at a few springs birch trees form small groves. The vegetation characteristic of central Kane County is shown on Plates 3, 4, and 9.

GEOGRAPHIC FEATURES

Major land forms.—Central Kane County is part of the Colorado Plateau province: a vast region of plateaus, rock terraces, cliffs, canyons, mesas, angular ridges, and broad mounds, drained by elaborately branched perennial, intermittent, and ephemeral streams. Most of the local geographic features are duplicated elsewhere in southern Utah, also in northern Arizona, where rocks similar in composition, attitude, and age have been subjected to the same processes of erosion for the same length of time. About 50 per cent of the region lies between 5000 and 6000 feet above sea level. The extremes of relief are Black Rock Point on the White Cliffs (altitude 6800 feet) and the mouth of Kaibab Creek (altitude 3800 ? feet). However, because the strata dip north and northeast this topographic interval of 3000 feet is much less than the stratigraphic interval; the sequence of the sedimentary strata between the bottom of the Kaibab Gulch and the top of the White Cliffs is as much as 4500 feet.

Though in detail intricate, on a regional scale the geographic pattern of central Kane County is fairly simple; it comprises two types of general topography separated by the Vermilion Cliffs, which, except where incised by a few canyon trenches, extend continuously from the Paria River westward across Kane County as a picturesque, nearly vertical wall, 1000 to 1500 feet high (Pls. 3, 4). South of this erosion escarpment, where the altitude above sea level averages about 4500 feet, the land has low relief—some of it substantially flat—,and except for short stretches at their heads the streams with gradients less than 30 feet a mile occupy inconspicuous runways in broad shallow valleys, and some of their courses are clearly discernible only at times of floods (Pls. 5, 6). From this general surface of low relief, and especially near the Vermilion Cliffs, rise mounds, mesas, and cuestas 10 to 100 feet high that mark the position of rock masses that so far have escaped the general denudation. In this area, however, uneroded bedrock is scarce; much of the surface is mantled by alluvium from distant sources or by-products of local rock disintegration.

In contrast to the generally flat lands south of the Vermilion Cliffs—in Kimball Valley and elsewhere along the Utah-Arizona boundary line—the topography of

the region that extends from the crest of the Vermilion Cliffs northward to the base of the White Cliffs is rough. On the Wygaret Terrace the rocks have been trenched by master streams and innumerable tributary streams which occupy narrow, flat-floored canyons and on emerging from the Vermilion Cliffs flow between nearly sheer walls 500 to 800 feet high. Generally on the Wygaret Terrace the intercanyon areas are characterized by low broad-based buttes of bare rock, rounded ridges, and gentle slopes, in places coated with soil, and on which here and there sand from the washes has been deposited as dunes. Conspicuous exceptions to this general expression are the isolated boxlike mesas along the crest of the Vermilion Cliffs, No Mans Mesa, and the magnificent Tabetimp (White Cone; Mollie's Nipple), a lonely outlier of the White Cliffs which rises more than 760 feet above the adjoining ridges. However, if the canyons were filled and the higher prominences erased, the area between the Vermilion Cliffs and the White Cliffs would be expressed in the regional topography as a plain of low relief with a northward inclination of 1°–3° and thus accord roughly with the attitude of the sedimentary beds.

Disregarding the regional pattern the outstanding geographic features of central Kane County are the White, the Vermilion, and the Shinarump cliffs which record the differential erosion of flat-lying sedimentary beds, and the Kaibab Plateau, the Coxcomb, and House Rock Valley which owe their form and residual altitudes to the upwarping of strata. As pointed out by Dutton and his associates long ago, the erosion of once-continuous, high-lying, horizontal sedimentary rocks in the region north of Grand Canyon has produced a stairway in which the treads measure the amount of soft rock removed and the risers the thickness of the hard rocks—individual strata or groups of strata similar in durability. In central Kane County the major steps are the Vermilion Cliffs, which rise precipitously about 1000 feet above the broad Kimball Valley, and the White Cliffs, 800 to 1200 feet high, which mark the northern boundary of the Wygaret Terrace. Below the Vermilion Cliffs, the Shinarump Cliffs, 100 to 300 feet high and conspicuous because of their color and steepness, cross Fossil Wood Wash and Seamans Wash and extend southwestward into Arizona (Pls. 1, 2). Because these lines of cliffs are far apart their features and relations are not everywhere discernible; generally in Kane County the view of the White Cliffs is blocked out by the Vermilion Cliffs. Farther south in Arizona on the slopes of the Kaibab Plateau, along U. S. highway 89, all these great escarpments, also the minor escarpments and benches, are visible; they appear as huge walls, attractive alike for their architecture and distinctive colors—one of the great panoramas of the plateau country. East of the Kaibab in House Rock Valley and at the mouth of Paria River, the White Cliffs, the Vermilion Cliffs, and the Shinarump Cliffs are close together; essentially they are benches in an otherwise vertical wall.

The Kaibab Plateau that dominates the topography of northern Arizona extends into Utah with little change in essential characteristics. In central Kane County it is represented by a broad nearly flat surface at an average altitude of 6000 feet and descends westward and eastward in conformity with the dip of the underlying rocks. The top of the plateau is dissected by swales and sink holes, and its edges are incised by widely spaced, deep, narrow, short canyons that lead to House Rock Valley and Johnson Creek. Remarkable features of the topography are Kaibab Gulch and

Sand Gulch, which, with the exception of the Colorado River, are the only drainage channels that cross the Kaibab Plateau and its southward extension, the Coconino Plateau, in a distance of about 200 miles in Utah and Arizona.

The Coxcomb is the crest of the narrow East Kaibab monocline, in which the strata have been upturned at angles as great as 50°. Near Adairville the structure stands about 1200 feet above the Paria River and with decreasing height and definiteness of outline extends across Kane County and far into Arizona. Like the Kaibab plateau, the Coxcomb is crossed by two streams that occupy narrow runways. From its broad valley at Paria, the Paria River plunges into Shurtz Gorge, 900 feet deep and less than 100 feet wide, and within a mile again flows over flat land. Sand Creek crosses the structure in Catstairs Gorge—a narrow, remarkably rough defile.

House Rock Valley is a conspicuous trench that separates the Kaibab Plateau from from the Coxcomb. It lies 500 to 1000 feet below the adjacent highlands. Essentially the valley follows the strike of tilted strata, and its development has been greatly facilitated by the general softness of the rocks along its course. For considerable distances the western border of the valley is clearly defined by the downturned beds of limestone that cap the Kaibab upwarp; its eastern border, by the eroded edges of strata involved in the East Kaibab monocline, or by the nearly horizontal strata that form the high-lying West Clark Bench (Pl. 9). The valley floor varies much in width and form. In places it is a mile wide and nearly flat; in other places it is narrow and crudely dissected. Locally hogbacks, cuestalike mesas, and fault blocks, exposed by differential erosion, rise from the floor; rock gorges sink below it. Though House Rock Valley is a continuous depression which slopes generally southward, it is not the course of a stream. In Kane County the waters that enter it are carried to Paria River and on to the Colorado by Sand and Kaibab creeks, which cross the valley nearly at right angles.

Streams and valleys.—The streams in central Kane County are parts of the Colorado River drainage system. About half of the run-off reaches the Paria River directly through short channels cut into its canyon walls or indirectly through Sand Creek and the long Park Wash and Deer Springs Creek which unite to form Kaibab Creek. The remaining run-off reaches the Kanab Creek after passing through Johnson Creek. In most places the boundaries of the Paria and Johnson drainage systems are poorly defined. Thus on the western Wygaret Terrace the long streams of low gradient that flow westward to Johnson Creek meet the short steep east-flowing tributaries to Deer Springs Creek on a surface marked by mounds, swales, open flats, and accumulations of drifting sands where the source and trend of running water are difficult to determine; on the flat top of the Kaibab Plateau the headwaters tributary to Kaibab Creek interlace with those in Johnson Creek; and in eastern Kimball Valley and elsewhere on the lowlands south of the Vermilion Cliffs some tortuous tributaries to Kaibab, Paria, and Johnson creeks are so placed that their relations are determinable only when the region is sheeted with water from heavy rains. In most places the Vermilion Cliffs is a conspicuous water parting; from their crest the drainage trends northward in channels of through-flowing streams of low inclination and southward through nearly vertical slots; only the Johnson, Deer Springs, and Kaibab creeks and the Paria River pass through the cliffs. Most

stream divides in central Kane County are shifting from the Paria River to the more favorably placed Johnson Creek drainage basins. On the way to the Colorado River the Paria River maintains channels through folds, but Johnson Creek encounters no structural obstacles. Furthermore, in about the same distance Deep Springs Creek, continued as Kaibab Creek and the Paria River, descends 5000 feet to the Colorado, and Johnson Creek, continued as Kanab Creek, 6120 feet.

In central Kane County the profile of most streams is a succession of relatively gentle and relatively steep gradients. For long distances the stream profile is smooth and nearly flat, but where rock floors the channels it is broken by steps that measure the thickness of the harder strata, commonly 3 to 10 feet. In crossing the Navajo sandstone at the Catstairs the bed of Sand Creek drops abruptly about 150 feet. In their course across central Kane County, Deer Springs Creek, continued as Kaibab Creek, descends about 70 feet a mile, Paria River 60 feet a mile, and Johnson Creek 40 feet a mile. In places these streams meander in shallow trenches across alluvium on gradients as low as 20 feet a mile. On the other hand some tributary streams that rise on the face of White and Vermilion cliffs rush down narrow grooves and over falls where gradients of 200 to 500 feet a mile are common, and short streams that score the flank of the Kaibab Plateau descend as much as 800 feet in a mile. Though the gradients of the major streams are generally less than for those of corresponding size in most adjacent regions, their interrupted profiles, scoured rock floors, and characteristically large load of rock waste indicate rapid erosion. All the streams are deepening their beds in alluvium and rock, sweeping away the enormous quantities of fine sediment that periodically clog their flow, and pushing along the coarser debris dumped into their channels by tributary gulches and land slides.

In developing their meandering courses and in modeling the landscape, the streams in central Kane County have been little influenced by the dip and strike of the strata. The chief control has been the composition and texture of the rocks encountered. The regional dip is north and northeast, but the major streams flow southeast, south, and southwest; only a few short streams along the south edge of the Wygaret Terrace and on the flanks of the Kaibab Plateau are adjusted to the dip of the rocks.

The relative resistance of rocks to erosion is shown along streamways where, during the same length of time, deep canyons have been worn into the massive and firmly cemented sandstones and limestones, and wide valleys in the less resistant shales. Between the Vermilion Cliffs and the Kaibab Plateau, where most of the rocks are soft, erosion has produced areas of essentially flat land. The effect of rock composition on rate and manner of stream erosion is also shown by the mesas, pinnacles, and stub-ended ridges—remnant masses of soft rock protected by durable caps. Downcutting by the short streams and for long stretches by the longer streams has involved chiefly the passage from one to another nearly horizontal bed of alluvium or rock. Conspicuous exceptions are presented by Kaibab and Sand creeks and the Paria River, which flow from one area of flat-lying strata to another through the upturned rocks that form the Kaibab Plateau and the East Kaibab monocline.

In central Kane County the stream channels are so distributed as to facilitate complete run-off, but the average precipitation is too small and too variable in time

and place to permit many streams to flow continuously. In normal years Johnson, Flood, Kitchen, Starlight, and Kaibab creeks, and the Paria River are through-flowing, though at times the bed of the Kaibab is dry for long stretches, and the Paria is reduced to a mere trickle. The long Park Wash and Deer Springs Creek and a few smaller streams are perennial at their heads and at places along their courses where springs emerge or bedrock is at or near the surface. By far the greatest number of streams in the region are ephemeral; they carry water only for short periods after rains.

Springs and lakes.—Springs are insignificant elements in the drainage system. Most of them are groups of seeps that issue from canyon floors at various levels or from the base of walls in alluvium or bedrock within areas of several hundred square feet; Rock Spring near Johnson is one of the few that emerge from a definite orifice. Of 12 springs measured in 1943—a year of normal rainfall—only the "Big Spring" at Johnson Lakes yielded as much as 6 gallons a minute; flows of less than 1 gallon a minute are more common. However, despite their size, small yield, and seasonal fluctuation, the springs on the Wygaret Terrace are invaluable sources of water for sheep and cattle, and south of Vermilion Cliffs the Seeps, Seaman, Clark, and Jepson springs, Jenney Clay Holes, and the historically famous Navajo Wells supply small amounts of palatable water for livestock and men. In pioneer days these springs made possible traverses by wagon across the arid lands between the settlements on Johnson Creek and the Paria River.

Though the region as a whole is thoroughly drained and the flow of perennial, intermittent, and ephemeral streams is generally unobstructed, some of the meadows in Stewart Valley are swampy, and ponds interrupt the otherwise continuous run-off in Lake Canyon and upper Kitchen Valley. Johnson Lakes—the largest about 2 acres in area—are fed by springs that emerge at the base of sandstone walls and by seeps in the alluvium of the canyon floor. These small lakes, though subject to seasonal and cyclical variations in volume, are perennial and since pioneer days have provided ample water for livestock that graze in the generally arid surrounding region. The ponds at the head of Kitchen Creek occupy low places on alluvium where the valley gradient is too flat to permit easy run-off and are fed chiefly by rain water and melting snow and therefore vary in volume and area in accord with cycles of heavy and light precipitation. It is reported that in pioneer days there were three "Kitchen lakes", each about an acre in extent and bordered by grassy meadows, and that since about 1885 they have been largely filled by stream wash. When visited in 1931 all the lakes were dry; and in the summer of 1943 they were represented by a shallow pond in which reeds and other water plants were growing. Unless artificially protected the bodies of standing water in both Lake and Kitchen valleys seem destined to short lives.

SEDIMENTARY ROCKS

GENERAL STRATIGRAPHIC RELATIONS

The sedimentary rocks in central Kane County are chiefly Triassic and Jurassic. Along Paria River a short narrow band of Cretaceous strata is exposed, and rocks of

Permian age line the deep canyons that cross the Kaibab Plateau. In physical composition, stratigraphic sequence, general topographic expression, and age the subdivisions of these rocks are the somewhat modified equivalents of those exposed elsewhere in southern Utah, and some are coextensive with the Colorado Plateau. Without significant change in character, the Permian and Triassic formations in Kane County extend westward in Utah to the Virgin River Valley and southward into Arizona, and the Jurassic and Cretaceous formations extend northward and eastward along the Paria River and the base of the Kaiparowits Plateau. In fact, throughout southern Utah, the stratigraphic features are so persistently characteristic that descriptions of formations in adjacent regions apply in most respects to central Kane County (Gregory, in press a, b; Gregory and Moore, 1931). Therefore in this paper stratigraphic discussion is restricted chiefly to distribution, general characteristics, and local variations.

PERMIAN FORMATIONS

General statement.—Permian rocks are exposed in canyons in the Kaibab Plateau—essentially the Kaibab upwarp. Along the eastern and western sides and at the northern edge of the plateau the steeply dipping Permian passes beneath Triassic and for long distances beyond is lost to view. Along the crest of the upwarp south of Road Creek these beds may be traced southward to the rim of the Grand Canyon of the Colorado, where they were mapped by the Powell and Wheeler surveys as part of the "Aubrey" group and assigned to the Carboniferous. More recently this roughly outlined group has been defined as comprising four stratigraphic units: the Supai formation (Pennsylvanian and Permian ?), the Hermit shale, Coconino sandstone, and Kaibab formation of Permian age. In central Kane County the Hermit shale was observed only at the bottom of Kaibab Gulch. The upper and, in places, the middle part of the Kaibab crop out in swales and shallow canyons on the surface of the Kaibab Plateau, and the entire formation is displayed in Kaibab Gulch in contact with the Hermit below and the Moenkopi formation above. (*See* Section 1.) In central Kane County rocks referable to the Coconino sandstone and the Supai formation are absent.

Hermit shale and Kaibab limestone.—The Hermit shale consists essentially of "red sandy shale and fine-grained massive friable red sandstone, which exhibits concretionary structure" (Noble, 1928). The Kaibab limestone varies much in composition and stratigraphic sequence. Though dominantly drab-gray or buff limestone, in beds 1 to 15 feet thick—commonly 2 to 6 feet—the Kaibab includes thick and thin beds of light-gray, white, and yellow beds of sandstone, shale, travertine, breccia, and conglomerate. Commonly the calcareous and arenaceous materials are poorly segregated, but in some places the sandy beds are interstratified with compact, nearly pure limestones—crystalline or amorphous calcite or dolomite. Conspicuous features of the limestone are the nodular aggregates and lenses of chert which in places make up a considerable part of the rock. Quartz geodes are fairly common. In the development of topography the Kaibab limestone has been an important control. Along the crest and upper slopes of the Kaibab upwarp its resistant limestone beds, exposed by the removal of weak overlying sediments, form continuous platforms that are incised by incipient erosion channels

and sink holes. Where deeply trenched by streams they stand as vertical cliffs broken into segments by joints and bedding planes, or as walls of slightly recessed steps, whose height measures the thickness of individual beds. Most canyon walls built of Kaibab strata show two or more vertical cliffs of compact cherty limestone separated by slopes of sandstone and sandy, calcareous shale.

The fossils collected during the survey represent the well-known fauna that characterizes the Kaibab limestone. They identify the formation as a Permian marine deposit and, considered in connection with the abundant sandy material, suggest near-shore, shallow-water environment.

A time break between the Kaibab limestone and the overlying Moenkopi formation is demonstrable, but its exact position is not everywhere easy to define. In places the interval is marked merely by weakly cemented, contorted, sandy shale, which on weathering produces grooves on canyon walls. Commonly interruption in deposition is shown by jumbled beds of brecciated limestone between thick-bedded resistant Kaibab limestone and the thinly bedded, more friable limestones of the Moenkopi formation. More rarely at the contact an uneven surface of compact limestone is covered by overlapping short lenses of resistant conglomerate composed of slightly weathered limestone, calcareous sandstones, sandy shale, chert, and rare pebbles of vari-colored quartzite. At the head of Kaibab Gulch calcareous shales, in which occur "productoid and martinoid brachiopods", assigned by G. A. Cooper to the Permain, lie less than 10 feet below coquina made of Lower Triassic gastropods and fragmentary ammonites. Likewise, in gullies that trench the eastern slope of the Kaibab upwarp, limestone and breccia, well stocked with diagnostic Permian fossils, directly underlie the fossiliferous limestones of Triassic Moenkopi (Pl. 3). The regional evidence suggests that sea waters receded from southwestern Utah in late Permian time and reappeared in early Triassic time, and that emergence and submergence produced little change in the physical character or the attitude of the sediments that constitute the Kaibab and the lowermost Moenkopi.

TRIASSIC FORMATIONS

Regional relations and subdivisions.—The most complete exposure of Triassic sediments in the Colorado Plateau Province is in the Virgin River Valley between Springdale and Virgin City, where the formations are displayed in two steep slopes, each more than 1500 feet high and clearly distinguished by color and manner of erosion. The lower slope, rising from a flat floor of limestone and continued upward by color-belted, thin-bedded sandstones, sandy limestones, and gypsiferous shales, includes all but the basal strata of the Moenkopi formation. The upper slope of brightly colored, intricately carved shales of variable composition, overlain by red sandstone, constitutes the Chinle formation. Between these two magnificent belts of rock lies the equally distinctive Shinarump conglomerate, a bed of gray sandstone less than 100 feet thick which forms cliff steps and tops of mesas. Eastward across southern Utah to the Paria River, and southeastward to Lees Ferry in Arizona, the arrangement of the Triassic strata along the Virgin River is maintained. The Moenkopi, Shinarump, and Chinle are present, though not completely expressed in terms of cliff and slope.

In central Kane County rocks of Triassic age, though widely distributed, have been

so elaborately eroded that the formations are nowhere exposed in unbroken sequence. Generally in the region northwest of the Kaibab Plateau the lowermost and uppermost beds of the Moenkopi formation, all of the Shinarump conglomerate, and the resistant upper sandstones of the Chinle formation remain intact, and along Lower Road Creek the entire Chinle formation is in view (Pl. 2, fig. 2). In contrast the

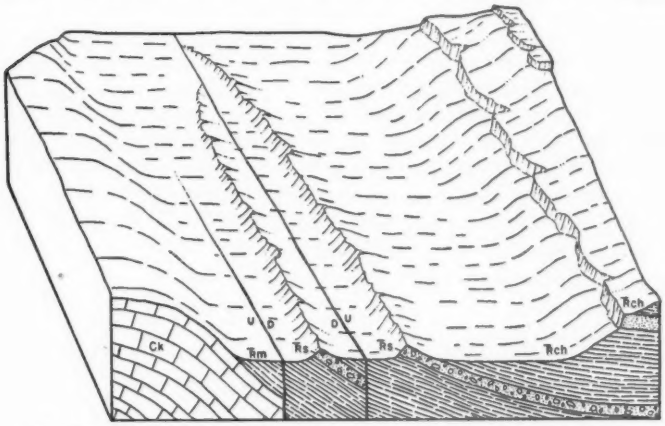


FIGURE 2.—*Cross section House Rock Valley near the mouth of Pine Hollow*
Constructed by Bronson Stringham

soft lower Chinle and middle Moenkopi have been largely removed by denudation and are now represented by disconnected mounds and ridges that rise above a debris-littered surface. In the House Rock Valley from the mouth of Sand Gulch southward the basal limestones and the topmost sandstones of the Triassic extend for long distances without interruption; here and there patches of gypsum in the Moenkopi and of variegated shales in the Chinle are conspicuous; from place to place tiny cuestas of Shinarump conglomerate rise from the valley floor. However, in places along the valley some of the formations have been cut out by faults or covered by landslides, alluvial fans, or stream wash (Fig. 2). In the absence of established topographic reference points, the time available was insufficient for classifying and fixing the position of the scattered outcrops. Therefore, on the geologic map (Pl. 1) the Shinarump and the Chinle formations in House Rock Valley are shown as a single stratigraphic unit.

Compared with its expression in other parts of the plateau country, the Chinle formation of central Kane County closely resembles that in Virgin River Valley but contains less limestone and much more sandstone than its type section in the Navajo country; the Moenkopi formation includes all the various groups of strata that characterize this formation in southwestern Utah but contains two, perhaps three, marine beds that are absent from outcrops in the Little Colorado Valley; the Shinarump conglomerate is finer in grain and contains less fossil wood than at most places in Utah and Arizona.

FIGURE 1. LOOKING EAST FROM PIONEER GAP
Across Seaman Wash, the Shinarump Cliff to the foothills and wall of Vermilion Cliffs. Trm, Moenkopi formation; Trs, Shinarump conglomerate; Trc, Chinle formation.

FIGURE 2. LOOKING NORTH FROM LOWER ROAD CREEK
Across Petrified Forest member (Trcpf) and the upper red sandstone member (Trcur) of the Chinle formation.

VIEWS ALONG VERMILION CLIFFS

Pk, Kaibab limestone; Trmt, Timpoweap member of the Moenkopi formation.

PERMIAN AND TRIASSIC ROCKS AT THE MOUTH OF LIMESTONE GULCH

The average measured thickness of the Triassic sediments in this area is about 2000 feet and thus exceeds the maximum thickness recorded for the Kaiparowits region (1075 feet), the San Juan region (1270 feet), the Navajo Country (1618 feet), and the San Rafael Swell (1245 feet) but is considerably less than that in the Zion Park region (3080 feet).

Moenkopi formation.—Though much of the Moenkopi formation in central Kane County is concealed beneath disintegration products and alluvium, enough is exposed to permit recognition of its general features and some of its specific features and also to indicate its structural relations, its age, and the conditions under which it was deposited. The widely spaced outcrops show that the formation consists predominately of dark-red and chocolate-brown sandstone, in beds which might appropriately be classed as shale—some of it as mudstone—and includes beds of limestone, gypsum, and lenticular conglomerate. The sandstone consists chiefly of generally well rounded, poorly sorted, fine- and medium-sized grains of quartz (90+ per cent), decomposed feldspar, and rare mica. It includes also lenses and scattered aggregates of conglomerate in which pebbles of limestone, sand nodules, and concretionary mud balls are conspicuous. The limestone is widely distributed as nodular, thin, compact lenses and small conglomeratic masses and assumes prominence at the base of the formation and a few hundred feet above where groups of calcareous beds are as much as 30 feet thick. Gypsum is common as original beds and secondary deposits in joint cracks. Of these sediments some seem to have been deposited in an open sea, some in bays and lagoons along the coast, and some in broad shallow valleys not far from the shore line. The shifts from marine to brackish water or to fresh-water conditions is marked in places by erosional unconformities, in other places by an abrupt or gradual change in the character of the sediments.

In southern Utah and northern Arizona the Moenkopi formation comprises units of strata sufficiently distinctive to justify their recognition as subdivisions or members. Though in composition these groups are not exclusive and their boundaries in many places are indefinite, as generalized lithic and color units they occupy the same relative position in all measured sections and record comparable changes in origin and manner of deposition. In Virgin River Valley, where the entire formation is exposed, the subdivisions have been studied in detail and named. Because all of them have been traced eastward to the Paria River the terminology of the standard section as applied by Reeside and Bassler (1922) and modified by Gregory (in press, a) has been adopted as suitable for central Kane County.

In outline the characteristic features of the six recognized subdivisions of the Moenkopi formations are as follows:

Shinarump Conglomerate: Upper Triassic

Unconformity

Moenkopi formation: Lower Triassic

6. *Upper red member.*—Shale and thin imbricated sandstone, brown and chocolate-colored, crossed by rare white bands; gypsiferous throughout and crisscrossed with seams and joint fillings of gypsum; ripple marks common. Weathers as fluted walls. Thickness 98–130 feet.

5. *Shinabkaib member.*—Gypsum, white, green white, and pink, much of it arenaceous; weakly cemented, poorly defined beds irregularly alternating with light-red gypsiferous shales; intricately dissected into bad lands. Thickness measured 138–236 feet; average estimated 180 feet.

4. *Middle red member*.—Sandstone generally red; calcareous and gypsiferous; thin regular beds, some lenticular and nodular; ripple-marked. Weathers into low mounds and flats. Average thickness 240 feet.

3. *Virgin limestone member*.—Marine limestone, dark gray; thin, markedly lenticular beds ½ to 1 foot thick, in places shaly; generally arenaceous; fossiliferous. Forms low cliffs and caps for mesas and ridges. Thickness 16–45 feet.

Unconformity (?)

2. *Lower red member*.—Sandstone, red and brown; imbricated, shalelike beds, some ripple-marked and sun-cracked; gypsiferous. Weathers as low steps. Thickness estimated 200 + feet (Pl. 4, fig. 1; Pl. 5, fig. 1).

1. *Timpoweap member*.—Upper part: shale, yellow, white, brown, and red; ferruginous, calcareous, arenaceous, and gypsiferous; includes calcareous sandstone in beds 1 to 3 feet thick. Lower part: limestone, gray and buff; hard, irregular beds; fossiliferous. Exposed as bare surfaces and the rims of canyons. Average thickness 170 feet.

Unconformity

Kaibab limestone: Permian

Viewed as groups of "Triassic red beds", the lower, middle, and upper red members of the Moenkopi formation are much alike; they have the same range in size of grain, in thickness and extent of individual beds, and in position and continuity of lateral disconformities. Sun-hardened surfaces, sun cracks, and the spoor of land animals (reptiles ?) indicate intermittent deposition, and the common ripple marks the presence of shallow water. Most of the sediments of these red members are believed to have been deposited by streams that traversed a coastal plain of low relief, but the included bedded gypsum and the thin lenses and aggregates of limestone that contain fragmentary marine (?) mollusks suggest that at times sea water or at least brackish water was present. Analyses of 14 samples from prospect trenches in the upper red sandstone of the Moenkopi are reported by Lawson (1913) to yield an average of 4 cents a ton of gold.

The Shnabkaib member of the Moenkopi is well exposed in central Kane County at Banded Butte and adjoining mesas and in cliffs that extend past the mouths of Sand Gulch and Kaibab Gulch, where the upper red beds and the Shinarump conglomerate afford protection (Pl. 4, fig. 2). Elsewhere the member has been disintegrated and in places reduced to a white powder, blown about by wind. The distinguishing features of the member are the white horizontal gypsiferous bands that, lying between red shales, decorate cliff faces, canyon walls, and may be traced across flat lands. These bands, commonly 6 to 20 in a series, and a few inches to 4 feet in thickness, roughly outline a distinctive stratigraphic unit, which, however, has no definable boundaries. The clearly marked gypsum and highly gypsiferous beds merge above and below into the less gypsiferous upper and middle red beds. The Shnabkaib is probably a marine, or at least a brackish-water, deposit. The widespread, thinly and evenly laminated gypsum and accompanying shales suggest deposition in the quiet waters of coastal lagoons.

The Virgin limestone member of the Moenkopi in central Kane County lacks the massive beds and the somewhat regular lamination characteristic of its type exposures near Virgin City, Utah. Though it includes thin, brittle beds of nearly pure fossiliferous limestone, as a whole it is highly arenaceous, very unevenly bedded, and its surface is roughened by geodic masses and circular indentations. Along the road from Pioneer Gap to Kaibab Creek the member in few places is more than 25 feet thick, whereas its average thickness in Virgin Valley is about 90 feet and in Kanab Valley 75 feet. Farther east in House Rock Valley the thickness is 4 to 6 feet and

in places only about 2 feet. Still farther east measured sections reveal no fossiliferous limestone in this stratigraphic position. Apparently the waters of a western sea shallowed eastward and reached their limits in the vicinity of the present Paria River.

The Timpoweap member of the Moenkopi, exposed on the flanks, and in places at the top of the Kaibab Plateau, consists of three unlike groups of strata: at the base, conglomerates and breccia; higher up, limestone; and at the top variegated shales (Pl. 3). The conglomeratic beds are unevenly distributed and remarkably variable in composition. The limestones are the rim rocks of many canyons and on intercanyon areas commonly form broad surfaces of bare rock, crisscrossed by conspicuous joints. The soft yellow, red, and gray shales generally have been stripped from the limestone but remain here and there in low ridges and rounded buttes. In color, style of bedding, and resistance to erosion the limestones in the Timpoweap are much like those that make up the Kaibab limestone, and in combination these two groups of resistant rock form the surface of the Kaibab Plateau. Doubtless because of this relationship and the paucity of diagnostic fossils, the different ages of the two limestones were overlooked by the geologists of the Powell and the Wheeler Surveys, by Darton (1925), and by other students (Noble, 1928; Gregory and Moore, 1931).

Recent studies show that the Timpoweap in central Kane County and westward to the Hurricane Cliffs is a definable stratigraphic unit which in age, and to a less degree in physical character, is unlike the normal Kaibab that lies unconformably beneath it. The basal Timpoweap beds, which have been dubbed "Kaibab limestone with Triassic fossils", are probably part of the sequence hitherto mapped as Kaibab in other parts of the plateau country.

Fossils in the Moenkopi formation of south-central Kane County, though few have been specifically identified, clearly represent the large fauna that in the Virgin River Valley fixes the age of the formation as Lower Triassic. In the spongelike masses of shell fragments from the Timpoweap member in Kaibab Gulch, Reeside (1943) recognized "Molds of various undetermined gastropods and the ammonite *Meekoceras*, Lower Triassic," and in studying fossils from Quarry Ridge in rocks mapped respectively as the Timpoweap and the Virgin limestone members of the Moenkopi formation he found that:

> "Both of these lots contain masses of gastropods similar to those in other collections found at a number of places in the lower part of the Moenkopi formation. None of them have ever been described but at many places they are associated with *Meekoceras*, which marks them definitely as Triassic. I have never seen any of these gastropods in the Kaibab."

Regarding fossils collected at the base, on the flanks, and at the top of the Kaibab Plateau along the Utah-Arizona boundary line Reeside (1945) remarks:

> "One lot, No. 5, is definitely Paleozoic. One lot, No. 4, was referred in the field to the Virgin limestone member of the Moenkopi and the fossils fit. The remaining three lots I would assign with some hesitation to the Triassic. There are no forms that I recognize as definitely Paleozoic and all present are similar to or identical with forms previously referred to the Moenkopi. Very few names have been applied to the gastropods of the Moenkopi and I do not feel that the effort to do so now would be worth the time it would take."

Even if the faunal evidence were less conclusive, correlation with Lower Triassic strata elsewhere in southern Utah is made with confidence. All established members of the Moenkopi formation may be traced from their type locality near Virgin City,

Utah, eastward to the Paria River. Along this belt their stratigraphic and physical features are remarkably persistent, and the boundaries of the formations remain constant: Upper Triassic Shinarump conglomerate above and Permian Kaibab limestone below. East of the Paria River the Moenkopi maintains its position among Triassic formations but is thinner and as reported includes no marine sediments. The type section in the Little Colorado Valley is less than 400 feet thick and lacks clearly defined beds of gypsum and limestone.

Moenkopi-Shinarump contact.—Where the contact is exposed the Shinarump conglomerate is obviously unconformable upon the Moenkopi. In places the contact is marked merely by an abrupt change in composition and style of bedding. In other places the top of the upper red sandstone beds of the Moenkopi presents broad grooves and minor shallow depressions, some of them partly filled with gravel before the Shinarump was deposited. Near the mouth of Road Canyon a stream channel in the Moenkopi has been filled by Shinarump sands (Pl. 5, fig. 1).

Shinarump conglomerate.—At its appropriate place in the stratigraphic column the Shinarump conglomerate is generally exposed in Kane County. It forms the face and back slopes of the Shinarump Cliffs and the cap rock of outlying mesas. For some miles east of Kaibab Creek it is largely concealed by talus and landslides, and farther east along the Vermilion Cliffs it is inconspicuous and in places may be absent. Near the mouth of Road Canyon, where it is upcurved in the East Kaibab monocline, the conglomerate is a conspicuous white band that separates the red Moenkopi beds from the brilliantly variegated Chinle formation. In House Rock Valley it is locally cut out by faulting, but in places its eroded remnants stand on the valley floor. The Shinarump is essentially a gray, or nearly white, boldly lenticular and cross-bedded, coarse-grained sandstone, generally strongly resistant but in places so weakly cemented as to weather readily into sand. It consists predominantly of rounded and subangular grains of quartz and quartzite less than $\frac{1}{8}$ inch in diameter and pebbles of quartzite, quartz, chert, and black limestone 1+ inch in diameter isolated or arranged in broken strings. In the sand are embedded worn fragments of petrified wood. The thinness, the relatively fine grains, and the abundance of regularly bedded sandstone and arenaceous shale that characterize the conglomerate along tributaries of the Paria River suggest that the streams of Shinarump time in central Kane County were much less effective in transporting than were those in regions farther south and east. In some parts of the plateau country this rock unit is made up almost exclusively of pebbles 2 to 4 inches in diameter.

Chinle formation.—Among the Triassic formations in central Kane County the widespread Chinle formation is easily recognized. As a sequence of brightly variegated shales and red and mauve sandstones that rest on the gray Shinarump conglomerate and continue upward to the light-red and tan Wingate sandstone, it forms the Vermilion Cliffs—one of the great escarpments of the plateau country. All about the abandoned village of Paria the lower part of the Chinle is displayed as the "painted desert", "rainbow buttes", and "artists' walls" [shown on moving picture screens in technicolor]. The Chinle exposed in the Paria River drainage basin is but a sample of a formation almost coextensive with the plateau province, and so persistent are its major features that stratigraphic sections measured at scores of

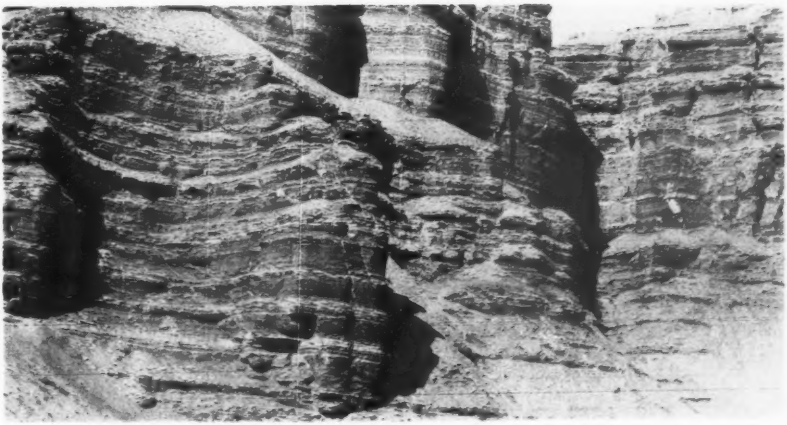


FIGURE 1. GYPIFORM SHALES OF THE LOWER RED MEMBER
Near mouth of Road Creek — gypsiferous shales.

FIGURE 2. SHNABKAIB MEMBER CAPPED BY SHINARUMP CONGLOMERATE
At Banded Butte.

VIEWS OF THE MOENKOPI FORMATION

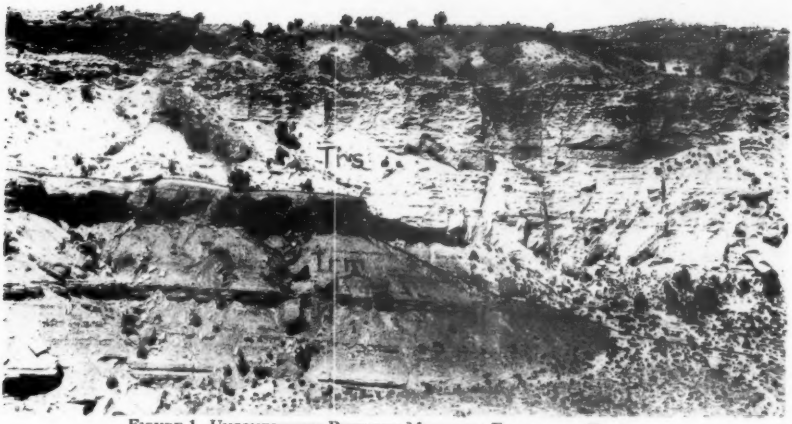


FIGURE 1. UNCONFORMITY BETWEEN MOENKOPI FORMATION (Trm) AND SHINARUMP CONGLOMERATE (Trs) WEST OF PARIA

FIGURE 2. PETRIFIED FOREST MEMBER OF CHINLE FORMATION
Showing style of erosion, head of Clark Wash.

places are substantially duplicates. Most directly applicable to central Kane County is the analysis of the Chinle in the Virgin River Valley (Gregory, in press, a), where the formation attains its maximum thickness and greatest variety of sediments and holds a characteristic fossil flora and fauna. Within the valley and about its borders the steep slopes and cliffs present four groups of beds sufficiently unlike in composition, color, and topographic form to justify their classification as stratigraphic subdivisions. At the base of the Chinle, merging downward into the Shinarump conglomerate, lie the lower sandstones, and above them in turn the Petrified Forest member, the Springdale sandstone member, and the upper sandstones that continue upward to the towering cliffs of Navajo sandstone. In central Kane County the four members of the Chinle are recognizable. The meagerly exposed lower sandstones show their usual features: coarse- and fine-grained, gray and brown, lenticular beds composed of angular and subangular grains of quartz (95± per cent), feldspar, mica, garnet, hard clay pellets, and carbonaceous material firmly cemented by gypsum, iron oxides, and dolomite (?). Likewise, the rare outcrops of the Springdale sandstone member are characteristic. They project as ledges, 10 to 30 feet thick, and consist of thick-bedded lenticular red sandstone, subordinate purple sandstone, fine quartz conglomerate, and greenish argillaceous shale—some of it ripple-marked and indented with reptilian tracks. However, the lower sandstones of the Chinle are very thin and in places not distinguishable from the topmost beds of the Shinarump, and the boundaries of the Springdale sandstone member are poorly defined. Therefore the Chinle formation in central Kane County consists substantially of the Petrified Forest member and the upper sandstones, which in combination make up most, in places all, of the Vermilion Cliffs (Section 3b).

The Petrified Forest member of the Chinle is commonly displayed as a congeries of mounds and rounded ridges, scarred by closely spaced gulches, some of which end in sink holes (Pl. 2, fig. 2; Pl. 5, fig. 2). In dry weather its outcrops are coated with incoherent, flourlike material, into which the foot sinks readily. During rains the fluffy stuff is rapidly removed, clogging channels with gray-blue mud, so fine-grained that after settling in camp buckets a third to half the material remains in suspension. Fragments immersed in water swell to twice their size and completely disintegrate. In distant views the member appears to be a heterogeneous mass of easily eroded material, mottled and brilliantly variegated in haphazard fashion—the material called by the pioneer geologist "marl". Closer examination reveals a pile of weakly consolidated coarse and fine quartz sands; gypsiferous, calcareous, and ferruginous silts; bentonite; muds of various composition arranged in overlapping and abutting sheets; tiny scattered pebbles of quartz, quartzite, and magnetite; hard black limestone; and concretionary calcareous nodules, rich in manganese. Persistent components of the Petrified Forest member are silicified fragments of conifers, which in places are sufficiently abundant to justify the term "petrified forests". At the head of Fossil Wash logs, chunks, and chips of "stone wood" are thickly strewn. They represent trunks, branches, and roots that have been abraded, broken, and splintered, probably while in transport; only a petrified tree stump near the mouth of Mine Gulch seems to remain where it grew. Careful search revealed no impressions of cones or leaves; the foliar parts, undoubtedly present, seem to have been

completely destroyed by oxidation. In fact, the only fossilized ligniferous fibers and macerated leaves reported from the Chinle are those found at Capital Reef in Wayne County (Gregory and Anderson, 1939).

The upper sandstones of the Chinle formation are roughly uniform in bedding and consist chiefly of red fine-grained dense resistant sandstone in beds 1 to 5 feet thick and sandy shale in groups 6 inches to 10 feet thick (Pl. 2). Within these stratified rocks variously oriented lenses, wedges, and disks of sandstone, argillaceous shale, and slightly gypsiferous mudstones make up groups 2 to 3 feet thick and 20 to 300 feet long that suggest local unconformities. The shales and some of the finer-grained, seemingly massive sandstone beds are subdivided into very thin imbricated layers, ripple-marked and sun-cracked. Measured sections show also lenticular conglomerates of hard bone-bearing limestones, jumbled fragments of sandstone and shale, concretionary spheres and pancakes of ironstone, and flattened clay balls. In the vicinity of Johnson Lakes several layers of compact or brecciated limestones are as much as 2 feet thick and form ledges on weathering. In addition to the dominant iron-coated quartz grains the member contains feldspar, calcite, and bits of tourmaline and pyroxene. The cementing materials are lime and iron. In many places the general dark-red tone of the sandstones is interrupted by white bands that seem to be systematically arranged. In Lake and Nephi canyons these bands make up a considerable part of the exposed rock and add a color pattern to the elaborately carved walls. At the head of Seaman Wash and elsewhere along the crest of Vermilion Cliffs the topmost red sandstones are embedded in thick lenses of extremely friable pure white sandstone composed of tiny spherical grains in a manner that suggests a once-continuous bed. Along the headwater branches of Boxelder Creek two or more of these white beds in short sequence at the top of the Chinle may represent a transitonal contact with the Wingate sandstone above.

The Chinle formation in southern Utah and equivalent beds in Colorado and Arizona have been industriously searched for metalliferous ores, chiefly gold, silver, and mercury. Prospect holes and placer claims in the Virgin River Valley and eastward along the Vermilion Cliffs may be counted by scores, and mines have been operated at several places. Only the unique Silver Reef mines near Leeds, Utah, have been profitable. As Lawson (1913) points out, the gold in the Chinle at Paria averages about 5 cents a cubic yard—a figure probably applicable to most outcrops of the formation. However, no successful method has been devised for extracting gold from the peculiar fluffy, pulpy, fine-grained sandstones, clays, limestones, and volcanic ash in which it occurs. In Mine Gulch a manganese deposit estimated as containing 70,000 tons of ore has been intermittently mined, but without financial success.

The Chinle formation in Paria River Valley is 860 to 1115 feet thick and at Flagpoint 1110 feet thick. The sections in Virgin River Valley, 60 miles to the west, measure 950 to 1380 feet and at Cedar City 1000–2000 feet. The type section at Chinle on the Navajo Reservation is 1182 feet thick, and within the drainage basins of the Escalante and Fremont rivers measurements of 200 to 600 feet are common.

In the geologic reports of the Wheeler and Powell surveys the "Upper Shinarump group" or "the Vermilion Cliffs series"—substantially the Chinle formation—is

described as the lower part of a thick series of marine Triassic sediments. Huntington and Goldthwait (1904) treated the "Painted desert formation" in southern Utah (Petrified Forest and Springdale sandstone members of the Chinle) as marine deposits of early Triassic age, and Branson (1927) thought of the widespread Chinle formation as part marine and part subaerial. However, the lithologic, stratigraphic, and paleontologic evidence demonstrates that the entire Chinle is terrestrial. The rocks reveal the presence of strong streams and weak streams, perennial and ephemeral streams, shallow bodies of fresh water, and surfaces exposed intermittently to the sun. In them are embedded tracks of land animals, saurian bones, terrestrial mollusks, fresh-water fishes, forest trees, and plants of lower orders. The Triassic age of the Chinle seems established, but some doubt remains regarding the appropriate position of the formation within that system; the fossils are not conclusively diagnostic. Nevertheless the recorded evidence favors an assignment to the Upper Triassic.

JURASSIC FORMATIONS

Subdivisions and regional relations.—In central Kane County the formations tentatively classed as Jurassic are the Wingate sandstone, Kayenta formation, and Navajo sandstone which together make up the Glen Canyon group. Those assigned without question to the Upper Jurassic are the Carmel formation, Entrada sandstone, and the Winsor formation. In stratigraphic sections rocks of Upper Jurassic age are easily segregated; they extend up to the Cretaceous Dakota sandstone and down to an erosional unconformity between the marine Carmel formation and the terrestrial Navajo sandstone—the topmost formation of the Glen Canyon group. The division between the basal formation of the Glen Canyon group (Wingate sandstone) and the topmost Triassic (Chinle formation) is much less plainly marked. Though in several parts of the plateau country the Triassic and Jurassic beds are unconformable, commonly their contact is gradational and has been so treated in most reconnaissance surveys. Thus the geologists of the Wheeler and Powell surveys recognized two groups of sandstones with a combined thickness of 1400 to 1700 feet, deposited without interruption and differing mainly in color and topographic expression, as occupying the interval between the "marine Jurassic" (Carmel) beds and "variegated marls" (the Petrified Forest member of the Chinle). The generalized sections of "Triassic" measured by Gilbert (1875) and by Howell (1875) in Paria River Valley obviously include the Navajo, the Kayenta, the Wingate, and the upper part of the Chinle, as those formations are now defined. Likewise Gregory and Moore (1931) classed parts of the Chinle formation as "Glen Canyon Group, undifferentiated". The difficulties in defining a division plane between Jurassic (?) and Triassic formations relate chiefly to the absence of specifically diagnostic fossils and the rarity of features that demonstrate pauses in deposition and coincident widespread erosion. These annoying conditions influence also the attempts to delimit the formations within the Glen Canyon group. In many places only changes in color and style of bedding mark the planes of separation between the Wingate and the Kayenta, and the Kayenta and the Navajo.

In southern Utah the maximum thickness of the rocks assigned to the Jurassic

is 3044 feet in San Juan River Valley; 4764 along Glen Canyon (includes about 1000 feet of strata not represented farther west); 3480 in Virgin Valley; and 2050 along the Hurricane Cliffs where its lower part is missing. As shown in measured sections, the Glen Canyon group thickens westward—from 1100 feet in the San Juan country and 1650 feet in the Kaiparowits region to more than 2000 feet in the Zion Park region. Regionally its major units exhibit systematic changes in thickness. Thus in southeastern Utah Wingate sandstone forms sheer massive walls 300 to 450 feet high, but west of Paria River it averages less than 150 feet thick and disappears in Virgin River Valley. Likewise, the Kayenta thins progressively westward and disappears in Zion Canyon. In contrast, the Navajo sandstone, as if to maintain the normal total thickness of the Jurassic, thickens westward and beyond Zion Canyon represents the entire Glen Canyon group. Measured sections show 400 to 880 feet of Navajo in the San Juan Country; 900 to 1400 feet in the Kaiparowits region; and 1800 to 2000+ feet in the Parunuweap and Virgin Valleys.

Glen Canyon group.—Because their relation and age have not been determined satisfactorily it has been found convenient to treat the rocks that lie between the Chinle formation (Upper Triassic) and the Carmel formation (Upper Jurassic) as the Glen Canyon group. This stratigraphic unit which includes the most conspicuous rock masses in the plateau country is believed to be Jurassic but its place in that system is doubtful and possibly its basal strata are Triassic. Its generally recognized subdivisions are Wingate sandstone, Kayenta formation and Navajo sandstone.

WINGATE SANDSTONE: The Wingate sandstone—the basal formation of the Glen Canyon group—is exposed in the canyon walls of Johnson Creek, Flood Creek, Kaibab Creek, Park Wash, and branches of Kitchen Creek. Along the crest of the Vermilion Cliffs it forms part of elongated mesas and here and there is the cap rock of broad ridges. Generally on the Wygaret Terrace the Wingate has been eroded from intercanyon surfaces, and in the walls of Paria Canyon, where its regional dip should bring it into view, no undoubted Wingate sandstone is recognizable. The sandstone varies from 10 to 30 feet thick in branches of Starlight Canyon, 80 to 90 feet in Deer Springs and Park washes, and 200+ feet in Johnson Canyon. The outcrops of the Wingate are thin but conspicuous; they are relatively resistant unfoliated masses of nearly white rock between red thin-bedded sandstones and shales. As a whole the Wingate is buff or white, massive, conspicuously cross-bedded, and divided into segments by prominent vertical joints. Here and there the general massiveness of the rock is interrupted by lenses of calcareous shales, thin compact limestone, and fine-grained conglomerate composed of fragmentary limestone and shale, clay pellets, and iron concretions (Pl. 6, fig. 2). The bulk of the rock consists of clean-washed translucent quartz grains (95+ per cent), tourmaline, feldspar, and aggregates of clay that vary in diameter from an average of about 0.12 mm. up to 0.70 mm. and down to microscopic grains—"blow dust". Most of the small grains are spherical or oval, and many of them are frosted or wind-etched like those in migrating sand dunes. The elaborate cross-bedding, the shape and size of grain, and certain minor features show that the Wingate is in large part an eolian deposit—the work of wind supplemented at times by streams. The erratic distribution and extreme variability

FIGURE 1. MASSIVE WINGATE SANDSTONE OVERLAIN BY KAYENTA FORMATION AT FIVE PINES

FIGURE 2. WINGATE SANDSTONE UNDERLAIN AND INTERBEDDED WITH CALCAREOUS SHALES AND LIMESTONE
Johnson Lakes.

WINGATE SANDSTONE

FIGURE 3. ALLUVIAL WALLS OF JOHNSON CREEK EXPOSED BY EROSION SINCE 1915.

FIGURE 2. WINSOR FORMATION
Ash Creek Valley.

FIGURE 1. NAVAJO SANDSTONE
North base of No Mans Mesa.

in thickness of the sandstone in central Kane County seem to mark the border of deposits, similar in character, that thicken northward and eastward.

KAYENTA FORMATION: On cliff faces and canyon walls where all members of the Glen Canyon group are represented, the Kayenta formation[3] is conspicuous as a belt of dark-red, foliated strata that separates buff or white unstratified masses—the Wingate and the Navajo. In the plateau province as a whole measured thicknesses of the Kayenta range up to 220 feet. In central Kane County the thickness recorded in six measured sections is 30 to 50 feet; in four sections, 10 to 60 feet; in three sections, 2 to 3 feet; and in places the formation is represented merely by a jumbled mass of sandstone and shale fragments. Though everywhere thin and highly variable in bedding, the Kayenta is relatively resistant to erosion; it covers large areas on the Wygaret Terrace from which the Navajo sandstone has been stripped away, and in the walls of many canyons and gullies it is the hard rim rock that protects the more friable Wingate sandstone.

The strata that make up the Kayenta are chiefly maroon sandstones and color-banded siltstone. Irregularly interbedded with these rocks are dense, blue-gray, white and pink sun-cracked limestones in layers a few inches thick, also thin beds of conglomerate composed of angular fragments of sandstone, shale, and limestone, clay balls, and concretions embedded in sand. The dominant sandstone consists almost wholly of fine, medium, and coarse rounded quartz grains, fairly well sorted, and includes bits of mica, white clay (decomposed feldspar ?), magnetite, limonite, and calcite. The chief cement is calcareous and ferruginous clay which around and between grains is so tightly compressed as to make the rock almost impervious; its contact with the Navajo sandstone is a zone of seeps. Regardless of their composition the beds are conspicuously lenticular; they overlap, thin to extinction, or end rather abruptly within short distances, and commonly groups of them are separated from one another, both vertically and laterally, by disconformities. Some lenses of coarse-grained rock occupy channels worn in rock of finer grain. The physical features of the Kayenta formation are characteristic of sediments deposited by streams in regions of low relief, streams subject to large seasonal fluctuation.

NAVAJO SANDSTONE: In central Kane County the Navajo sandstone is displayed as the magnificent White Cliffs and its huge outlying mesas and towers. From Johnson Canyon to the westernmost northern branch ("North Swag") of Kitchen Canyon, it forms a continuous escarpment except where crossed by the canyons of Deer Springs Creek and Park Wash. East of No Mans Mesa, where a low broad fold has uparched the Mesozoic beds, the Navajo has been stripped back southward from the rims of Sheep and Paria canyons to the crest of the Vermilion Cliffs, leaving only Tabetimp and the boxlike mesas along the headwater branches of Boxelder Creek. South of the Vermilion Cliffs at the Coxcomb the uptilted beds of Navajo

[3] When first described the sequence of red calcareous shales that separates the Wingate sandstone from the Navajo sandstone was termed the Todilto formation (Gregory, 1917). In the belief that the Todilto is some undefined part of the Morrison formation, the term Kayenta was substituted (Baker, Dane, and Reeside, 1936). A restudy of the field evidence suggests that the Todilto occupies the stratigraphic position originally assigned (Goldman and Spencer, 1941) and "is well below the base of the Morrison." Baker and his coauthors further postulated the absence of the Kayenta (= Todilto), also the Wingate in the Paria Valley and westward across southern Utah. Seemingly in their view the rocks here assigned to these stratigraphic subdivisions are properly classed as parts of the Chinle formation.

sandstone are the core rocks of the East Kaibab monocline, and near the Utah-Arizona boundary the sandstone in horizontal position forms the broad surfaces into which lower Kaibab Creek and the Paria River have sunk their canyons. Because in most places the sandstone exceeds 1000 feet in thickness and is essentially one fairly friable bed of uniform compositon and texture, its erosion forms are distinctive. Where overlain by the resistant limestone of the Carmel formation outcrops of the Navajo are characterized by nearly vertical cliffs and narrow, deep, box-headed canyons. Where this protective cover has been removed the sandstone weathers into smoothly modeled mounds, broad-based conical towers, and "nipples", separated by broad, very shallow, poorly defined streamways. In detail, erosion has produced the arches, window panels, cliff caves, waterpockets, and other picturesque features which have made exposures of the Navajo attractive as scenery and of special interest to students of erosion forms (Pl. 7, fig. 1).

The Navajo sandstone is fine-grained, remarkably even-textured, and consists essentially of white, crystal-clear quartz grains (95+ per cent) loosely held together by lime intermingled with iron oxides. Cloudy feldspar, magnetite, mica, tourmaline, and garnet are sparsely distributed, and small lenses of mineralized material contain azurite and malachite. Most of the minerals, especially the quartz grains, are spherical; many are frosted, and faceted or etched. About 70 per cent of the grains measure 0.10 to 0.25 mm. in diameter, and 25 per cent are very small, some of them microscopic. Included in the sandstone are lenses of dolomitic limestone that weather into shelves, and locally the resistant cement of iron and manganese (?) oxides slows up the normal rate of disintegration. Thus the isolated tower Tabetimp owes its preservation to the unusual abundance of iron-rich concretionary material, in zones 1 to 5 feet thick; ironstone in the form of lenses, disks, balls, stove lids, pancakes, and dumb-bells are embedded in the sandstone and make up much of the talus. The Navajo sandstone is cross-bedded on an amazing scale, more completely and intricately than any other formation in Utah. Horizontal surfaces, slopes, and vertical cliffs are crossed and recrossed by curves tangent to other curves and by series of variously oriented straight lines that truncate series differently orientated.

The Navajo sandstone like the Wingate sandstone is believed to be essentially the record of wind work. A marine origin is inconsistent with the faunal evidence; the fossils represent animals that lived on land or in shallow fresh-water lakes. Also, running water seems to have taken little part in accumulating the sands in the Navajo; the stratification and the assortment of material incident to stream deposition are almost absent. The shape, size, and arrangement of the grains and the intricate cross-bedding characteristic of the Navajo also characterize migrating sand dunes in adjacent regions.

Upper Jurassic formations.—In the Paria River Valley the stratigraphic interval between the typically developed Navajo sandstone (Middle Jurassic (?)) and the Dakota sandstone (Cretaceous) is occupied by roughly definable groups of brightly colored, dominantly arenaceous strata whose regional relations and mass characteristics justify their recognition as Upper Jurassic. Between Shurtz Gorge and the Catstairs these rocks are steeply upturned in a narrow belt on the flank of the East Kaibab monocline and are in process of dissection; the short swift streams that head

in the Coxcomb are rapidly developing a terrane of intricately interlaced gullies and ridges. Generally south of Sand Creek, where the effect of the monoclinal upwarp is barely noticeable, the Jurassic is expressed in the topography as gentle slopes and as broad, essentially level highlands cut into wide strips by canyons (Pl. 9, fig. 1). Here stream erosion is conspicuously slow; slopes of moderate inclination are thickly strewn with gravel, and the flatter lands are coated with disintegrated rock and windborne sand. On West Clark Bench the present ephemeral streams in poorly marked courses seem unable to remove the products of local weathering. However, erosion in this part of Kane County has been long-continued and effective; all the Tertiary and most of the Cretaceous have been worn away, and the Upper Jurassic beds retain their full thickness only where protected by a caprock of resistant Dakota sandstone.

The Upper Jurassic rocks represented in central Kane County are traceable through disconnected outcrops northward along the East Kaibab monocline, and the topmost beds eastward beyond the Paria River—in the latitude of White House Spring. Farther north and west in the upper Paria and middle Parunuweap valleys rocks in corresponding positions are displayed as an uninterrupted sequence of limestone, sandstone, shales, and gypsum—the components of the Carmel formation, the Entrada sandstone, the Curtis formation, and the Winsor formation (Gregory, in press, b). Of these four stratigraphic units that appear to constitute the upper Jurassic of southwestern Utah, the Carmel, the Entrada, and the Winsor are believed to be represented in central Kane County, but the boundaries are vaguely definable, and their physical features are but broadly characteristic.

As a whole the Upper Jurassic of central Kane County comprises three divisions based chiefly on topographic expression and dominant color. The lowermost division consists essentially of thin, unevenly bedded, friable sandstone and compact mudstone and includes flat lenses and oblong masses of small angular pebbles. Toward its base line cement is increasingly common, and thin limestones interlayered with deep-red thin sandstone are plastered over the uneven surface of the Navajo sandstone. The stratigraphic position and certain other features of this group suggest the Carmel formation of the Kaiparowits Plateau. The middle division is characterized by a sequence of relatively thin-bedded, dominantly red and maroon, slightly gypsiferous sandstones and shales, which in places are interbedded with white, gray, or yellow thick-bedded or massive sandstone. Similar rocks in the upper Paria Valley have been mapped as Entrada sandstone. The uppermost division consists of medium-grained very friable sandstone in thick massive white beds that are separated by beds of dark-red and green-white sandstone 3 inches to a foot thick, and thus produce the appearance of a white cliff unevenly banded with red (Pl. 7, fig. 2). Of the formations in southern Utah this division most closely resembles the Winsor. Though these three stratigraphic divisions are generally distinctive in color tone and manner of erosion—especially in distant views—their thickness is highly variable, their composition and texture irregular, and their parting planes obscure. The measured sections are but roughly comparable, and their correlation is subject to much doubt (Sections 5, 6). The Carmel may contain considerable limestone or none; it is uniformly gray or crisscrossed by white bands. The Entrada along Sand Wash is represented by about 70 feet of shalelike arenaceous beds which separate white sandstone 100+ feet

thick and traceable for a mile from an equally thick, massive yellow sandstone which changes along strike into coarse arenaceous shale. In the Winsor the width and spacing of the characteristic color bands follow no established system.

Absence of persistent stratigraphic features and of fossils makes the correlation of the Upper Jurassic formations in central Kane County far from satisfactory. In conformity with their type sections, the Carmel and Entrada lie successively above the Navajo sandstone and despite their dominantly local expression show an overall physical make-up more like their supposed equivalents than any other formations in southern Utah. The regional relations of the Winsor are especially difficult to define. In the time scale this formation occupies the position of the Morrison formation, but in other major respects it is radically different. The typical Winsor consists essentially of evenly stratified, friable sandstones remarkably uniform in texture and includes no representatives of the variegated shales, the coarse lenticular sandstones, or the volcanic debris that characterize the Morrison. Mapping shows that the Morrison, fully exposed in southeastern Utah, disappears before reaching the Paria River, and along this course the Summerville formation is generally absent, and the Carmel and in places the Entrada little resemble their typical exposures. Regional studies suggest that the peculiar composition and arrangement of the Upper Jurassic formations in central Kane County record a change in sedimentation—in part at least—from terrestrial to marine. Westward across southern Utah, formations in comparable position contain an increasingly rich marine fauna (Carmel and Curtis formations); eastward they are fluviatile and lacustrine in origin and include eolian rocks.

CRETACEOUS FORMATIONS

In central Kane County rocks of Cretaceous age are meagerly represented. The Upper Cretaceous Dakota sandstone and the Tropic formation occupy a narrow belt along the Paria River between Shurtz Gorge and Sand Creek. These scattered outcrops mark the western limit of the extensive, thick Cretaceous in the adjacent Kaiparowits Plateau.

As exposed north of Adairville the Dakota sandstone, 40 to 60 feet thick, consists chiefly of lenticularly bedded coarse-grained quartz rock within which lenses and strings of conglomerate are irregularly distributed. It contains also clay shales and an unusual amount of coal, some of it of commercial value. The Tropic formation, of which only the basal beds remain intact, presents its characteristic features: brown and yellowish sandy clay shales, three or more beds of coal, and an abundance of such Upper Cretaceous fossils as *Ostrea prudentia* and *Gryphaea newberryi*.

STRATIGRAPHIC SECTIONS

SECTION 1.—*Kaibab Gulch*

Measured by Levi F. Noble (1928) (U. S. Geol. Survey Prof. Paper 150, 1928)

	Feet
[Timpoweap member of the Moenkopi formation]	
Very irregular beds of coarse breccia-conglomerate, interstratified with buff shale and calcareous sandstone and capped by massive beds of buff limestone; the limestone forms a strong cliff; the shale and sandstone form a slope broken by irregular cliffs of breccia	77
[Unconformity]	

[Kaibab limestone]

	Feet
Massive gray crystalline limestone, cherty and fossiliferous, containing a bed of sandstone in the middle and passing at top into alternating beds of chert and buff earthy limestone; the beds of gray crystalline limestone form strong cliffs; the alternating beds of chert and buff limestone above the gray limestone form a steep, ledgy slope....	326
Buff and reddish fine-grained sandstone, poorly consolidated and irregularly bedded, interstratified with beds of sandy breccia and travertine; forms slope.....	150
Massive buff siliceous limestone, cherty and somewhat fossiliferous, containing some calcareous sandstone near the middle and a well-defined bed of hard fine-grained buff cross-bedded sandstone near the base; all beds except the calcareous sandstone in the middle of the member form strong cliffs.....	119
Alternating beds of arenaceous limestone and irregularly bedded fine-grained buff sandstone; one thin bed of limestone, in the middle of the member, is very fossiliferous; the member forms a steep, ledgy slope, broken by small cliffs.....	45
Total Kaibab limestone	717

Hermit shale.

A restudy of the rocks in Kaibab Gulch shows that the topmost 77 feet of Section 1 is unconformable upon the strata below and that the breccia and the cliff-making limestones contain Triassic fossils characteristic of the basal Moenkopi.

SECTION 2.—*Cliff near Banded Butte*

	Feet
Shinarump conglomerate	
5. Sandstone, gray; coarse-grained, lenticular beds in part cross-bedded; includes strings and aggregates of quartz and quartzite pebbles less than an inch in diameter and some fossil wood. Forms cap of mesas.....	20+
Unconformity	
Moenkopi formation	
Upper red member	
4. Sandstone and mudstone, red and brown; medium- to fine-grained; thick and thin beds subdivided into imbricated layers, some ripple-marked and sun-cracked; many lateral unconformities; includes rare pellets of clay and concretionary limestone.....	38
3. Sandstone, banded red, gray, and tan; thin fine-grained layers, slightly gypsiferous; forms steep slopes.....	60
Shnabkaib member	
2. Shales, unevenly banded, pale red and white; arenaceous, argillaceous, and gypsiferous; some beds ripple-marked; grades into nos. 1 and 3.....	53
1. Shale and gypsum, alternately banded cream white, pink white, and pale red, rarely drab; very thin beds, ripple-marked and sun-cracked; gypsum in thin, flat, and crinkled layers a fraction of an inch thick, more abundant near the top. Forms intricately dissected bad-land slope. Part exposed.....	85
Total measured	255

SECTION 3.—*Vermilion Cliffs along road Canyon*

	Feet
Chinle formation	
Upper sandstones	
7. Sandstone and arenaceous shale, light red, buff, and green white, irregular beds 3 inches to 6 feet thick; generally fine-grained and calcareous, includes lenses of bone-bearing limestone, conglomerate, mud balls, and strings and aggregates of small quartz and quartzite pebbles; weathers as cliffs. Thickness, in part estimated.....	580–700
Petrified Forest member	
6. Shales and "marls", variegated, overlapping lenses, imbricated sandstone, gypsum, limestone, and mud-ball conglomerate, bentonite, strings, and aggregates of clean-washed quartz pebbles; some petrified wood and worn bones. Like No. 4.....	220–260
5. Sandstone, buff and white: cross-bedded groups of lenses very irregularly interbedded with soft mud shales; includes discontinuous layers of hard, fine-grained green sandstone and accumulations of siliceous pebbles; thins and thickens along strike.....	12–20

4. Shales, brightly banded, in places blotched with white, yellow, lilac, green, and gray; arenaceous and gypsiferous; includes lenses of yellow conglomerate in which worn fragmentary bones are conspicuous; fossil wood in small amounts, much of it incompletely lithified. Forms steep cliff with benches	20–30
3. Sandstone, brown and gray; quartz grains of medium size cemented by gypsum, lime, and silica; contains layers of argillaceous shales and concretionary limestone; the base in contact with the Shinarump includes lumpy aggregates and thin long lenses of clay shale. Forms irregular bench	40–60
Total Petrified Forest member	382–452
Total Chinle formation	872–1070
Shinarump conglomerate	
2. Sandstone, light gray; coarse spherical and subangular grains of glistening quartz; weakly cemented by calcite; includes lenses, strings, and isolated individuals of varicolored subangular quartzite, quartz, and rare limestone pebbles as much as half an inch in diameter; fossil wood, some of it lignitic, weathers as cliff and disintegrates into a white powderlike sand	0(?)-40
Unconformity; marked by erosion.	
Moenkopi formation	
1. Shales, chocolate-colored, a few white horizontal bands, evenly bedded; sandy; gypsiferous; fine grains of quartz; many beds of small imbricated disks, many ripple-marked; outcrop crisscrossed with seams and crack fillings of secondary gypsum; resembles the Moenkopi at its type section in the Little Colorado Valley; forms vertical fluted walls; near the mouth of Road Creek disappears beneath the other formations in the Kaibab upwarp	0–220
Total thickness measured	872–1330

Unit No. 7 summarizes the features of the upper sandstones as revealed in four sections spaced about a mile apart. In field notes 8 to 12 subdivisions are recorded for each section, but no persistent planes of separation were found. Seemingly comparable outcrops of sandstone and shale occupy different stratigraphic positions, and the limestone and conglomerates are capriciously distributed.

SECTION 4.—*Park Wash near the mouth of Five Pines Gulch*

Dip 3° ± NE.

	Feet
Carmel formation; Upper Jurassic	
Unconformity	
Navajo sandstone	
4. Sandstone, light red or buff, in places white; massive; fine spherical quartz grains of uniform size, and rare subangular grains of magnetite, augite, and garnet; weakly cemented with lime and iron oxides; some grains etched. Contains iron concretions that cap short columns; lower part weathered into rounded knobs that form foothills of the main mass of No Mans Mesa	1600
Kayenta formation	
3. Sandstone and shales, dark red; thinly, unevenly bedded; in places knobby; coarse and fine-grained; includes lenses of conglomerate composed of concretionary limestone and clay pellets; strongly contrasted with nos. 2 and 4 in color and general lithologic characteristics	2–60
Wingate sandstone	
2. Sandstone, light red; fine round grains of quartz; in places even-bedded, elsewhere massive and cross-bedded on small scale	10–200
Unconformity: top of No. 1 eroded	
Chinle formation	
1. Sandstone, red and mauve; rough beds 1 to 6 feet thick; includes some layers of clay shale and thin lenses of limestone in which bones are embedded; part exposed	300+
Total thickness	2160

SECTION 6.—*Lower Shurtz Gorge about ½ miles below the town site of Paria*

Rocks dip 30° 40° S.E.

Measured by Bronson Stringham

	Feet
Cretaceous	
Dakota sandstone	
Conglomerate lenses in sandstone. Buff color. A few thin coal seams near basal contact	
Unconformity	
Upper Jurassic	
9. Sandstone, cream to buff; grains uniform, small, and very loosely cemented; crossed by red bands 1 inch to 3 feet thick, and appear or disappear along the strike. Bedding otherwise not apparent	125
8. Sandstone, cream to buff; cross-bedding prominent with a maximum height of 6 feet; grains uniform and small. Crossed by inconspicuous pale-brown and yellowish streaks	35
7. Sandstone, alternating white and red	126
a. Sandstone, white, of medium fineness; very loosely consolidated; bedding obscure; clay impurities seem abundant; weathering produces a hard muddy surface crust	93
b. Sandstone, reddish brown, very fine-grained; loosely consolidated; a little red clay material	18
c. Sandstone, like a	3
d. Sandstone, like b	4
e. Sandstone, like a	8
6. Sandstone, white; massive; cross-bedded; medium-grained; contains many small limonite concretions. Weathers in cliffs and nobs	325
5. Shale, red; sandy; weathers as small splinters; rather continuous along the strike	4
4. Sandstone, white; loosely consolidated; cross-bedded; marked by pale-greenish streaks	65
3. Sandstone; predominantly red; interbedded with white to pale-green sandstone and fine-grained, red, splintery shale; white beds and lenses ½ inch to 5 feet thick; occasionally red alternate with white beds to form a variegated surface	312
2. Sandstone, white; medium-grained; interbedded with red sandy shale; predominately white beds 6 inches to 15 feet thick, red beds 2 inches to 3 feet thick. Bedding everywhere well developed. Some beds near the base cemented well enough to form small cliffs	205
1. Sandstone, deepest red near the base, massive; medium-grained; includes thin beds of splintery shale; white bands are common near the top; near the base sand grains quite coarse and fairly well consolidated, and in places form low cliffs	185
Total measured	1382
Unconformity	
Navajo sandstone	

In interpreting this section Professor Stringham tentatively classed nos. 7, 8, and 9 as Winsor; nos. 2 and 3 as Entrada; and no. 1 as possibly a shore phase of the Carmel.

SECTION 6.—*West bank of Paria River near White House Spring*

	Feet
Pliocene (?)	
11. Conglomerate, dark gray; chiefly thick and thin slabs of exotic sandstone, 2 to 10 inches in long diameter; includes pebbles of variegated quartzite, limestone, and igneous rocks. Forms the resistant cap of a group of mesas. May represent the Parunuweap formation (Pliocene?)	20–50+
Unconformity; probably represents massive white sandstone as much as 400 feet thick.	

Jurassic

Winsor formation

10. Sandstone, alternately red and white; northward along strike white beds predominant; evenly bedded or lenticular on a small scale; chiefly fine, well-rounded grains of quartz; near the top conspicuous gray lozenge-shaped concretionary (?) masses, which on weathering leave tiny cliff caves. Forms slopes interrupted by low cliffs continuous for miles. Thickness estimated	220
9. Sandstone, white streaked with red; very poorly exposed	36
8. Sandstone, white, thin-bedded; largely covered by gravel	43
7. Conglomerate, composed chiefly of rounded quartzitic pebbles ¼ to ¾ inch in diameter. Small isolated outcrops; may be cemented surficial gravel	7
6. Sandstone concealed by coarse gravel	80
5. Sandstone, white with few streaks of red	12
Total Winsor formation	448

Entrada(?) sandstone

4. Sandstone, dark red; composed of quartz (95 per cent), feldspar, mica, and magnetite, cemented by lime carbonate and iron oxides; arranged as thin lenses, lumps, and tiny concretionary aggregates; includes bands of shale and of yellow coarse-grained sandstone 4 to 6 inches thick	42
3. Sandstone, white, in places yellow; generally massive, and cross-bedded; friable, weathers as powder; glistening, spherical grains of medium-fine quartz; cross-bedded; parts of it streaked with red sandstone of same composition. Forms a steep slope, in places a cliff, and weathers as low conical towers	36
Total Entrada(?) sandstone	78

Carmel formation

2. Limestone, pink on fresh surfaces, very thin-bedded; sandy; breaks into hard thin chips. Forms cliff	1–4
1. Sandstone, gray; very unevenly bedded; small, round, and subangular grains uniform in size, quartz cemented with lime, some calcite grains and rare lenses of limestone. Forms slopes	28
Total Carmel formation	28–32
Total measured	558

Unconformity

Navajo sandstone; forms walls of Paria Canyon

STRUCTURE

DISTRIBUTION OF FAULTS AND FOLDS

The outstanding structural features of central Kane County are the prevailing northeasterly dip of the strata, the Paunsaugunt fault, the Kaibab upwarp, and the East Kaibab monocline. Less conspicuous than the major displacements and much less effective in modeling the topography are the Swallow Park fault, which passes No Mans Mesa and dies out in the hills north of Kitchen Creek, the broad low folds on the Wygaret Terrace, and the faults with displacements of 5 to 50 feet that interrupt the continuity of the Jurassic sandstones north of Tabetimp, the Chinle formation along the face of the Vermilion Cliffs, and both the Chinle and the Moenkopi formations in House Rock Valley. Wherever observed these minor faults are vertical or inclined steeply westward and have their upthrow on the east. They appear to be simple fractures, in a few places accompanied for short distances by parallel fractures. Some of them are restricted to a single formation.

PAUNSAUGUNT FAULT

The "small fault" noted by Howell (1875) "about 20 miles to the west of Paria" is part of the Paunsaugunt fault which extends for 120 miles across central and southern Utah, and in Arizona seems to die out but may be represented by the West Kaibab fault, traceable to the Grand Canyon of the Colorado River. Like the Hurricane and the Sevier faults, the Paunsaugunt fault is a major zone of displacement in the plateau country; it has broken all the exposed Paleozoic, Mesozoic, and Cenozoic formations and has taken the leading part in the development of the present landscape.

The topographic inequalities produced by movements along the Paunsaugunt fault are most conspicuous at the head of the Paria River and northward where the upthrown block—the Aquarius Plateau—stands as much as 2000 feet above the downthrown block. In central Kane County the average displacement decreases rapidly southward. In the White Cliffs it is 1150 feet; in the Vermilion Cliffs 270 feet; and southward across the flat Kimball Valley, where its trace is concealed, probably not more than 150 feet. Generally on the Wygaret Terrace the topographic inequalities produced by the fault have been largely erased. In the valleys of Wildcat and Nephi canyons—short western tributaries to Deer Springs Canyon—the zone of faulting is represented by a belt of fractured Navajo sandstone and a discordance in the surface topography. At Hamblin Springs the upthrown block stands as a low cliff, and the strata in the downthrown block are tilted at various angles and in places crushed. In the Vermilion Cliffs erosion has lowered the upstream block to a level below the downthrown block.

Faulting at the canyoned head of Seaman Wash has conspicuously interrupted the continuity of the Triassic formations; east of a narrow belt of fracture the Shinarump conglomerate, the Chinle formation, and the upper part of the Moenkopi formation stand as much as 265 feet higher than the corresponding stratigraphic units on the west. In places the Shinarump conglomerate abuts against the Shnabkaib member of the Moenkopi formation, and the upper red sandstones and the Petrified Forest member of the Chinle formation are in horizontal contact. Generally along the wash the fault movements seem restricted to a plane or a very narrow belt, and the immediately adjacent strata retain their normal regional dips, but in the Vermilion Cliffs, where the zone of disturbed rocks is about half a mile wide, the strata on the downthrow side of the main fracture dip 12° to 20° W., and most of those on the upthrow side tilt slightly eastward. Included in the zone of fracture are variously oriented blocks as much as 100 feet wide and 200 feet long. Fracture joints in the Paunsaugunt fault zone favor the emergence of ground water at Wildcat, Nephi, Hamblin, and Seaman Springs—outlets for ground water little affected by climatic fluctuations.

KAIBAB UPWARP

The Kaibab upwarp—substantially the Kaibab Plateau—is the largest and the most lofty of the highland masses between the Grand Canyon and the High Plateaus of Utah. The upwarp is an expanse of uparched sedimentary rock, about 75 miles long and 20 miles wide, which rises abruptly 1500 to 2000 feet above the adjoining

lowlands. From the maximum altitude of 9200 feet (in Arizona) the surface of the plateau slopes gently northward and as a clearly definable topographic feature terminates at Road Creek—approximate altitude 4700 feet. Beyond this streamway the upwarp is represented by a broad, very low anticline that involves the Upper Triassic and Jurassic strata as far north as the White Cliffs, where it seems to die out or to be replaced by an inconspicuous fold that trends nearly east-west.

In central Kane County, particularly near the Utah-Arizona boundary, the form of the plateau is in close accord with the attitude of the rock. The nearly horizontal Permian and basal Triassic strata that cover the plateau at an average altitude of 6000 feet dip westward and eastward to positions 1000 to 1500 feet lower. Within a mile, in places half a mile, dips may change from less than 2° to as much as 20°. Along the west rim of the plateau dips of 10° to 30° were measured between the State line and Kaibab Creek, and dips of 4° to 8° were tested farther northeast. From the base of the plateau westward the dips progressively decrease and in the foothills of the Vermilion Cliffs merge with those characteristic of the undisturbed sedimentary rocks in southern Utah. The eastern flank of the Kaibab upwarp also is marked by abrupt conspicuous changes in dip. The resistant Kaibab limestone and the Timpoweap member of the Moenkopi are downbent at angles of 12° to 20°, and erosion of the soft overlying beds has left them standing as the prominent "Buckskin Cliffs", which form the west wall of House Rock Valley from the mouth of Sand Gulch far southward into Arizona. Unlike the progressive flattening that characterizes the west flank of the Kaibab, the dips of the strata along the east flank increase across House Rock Valley and attain a maximum of about 60° in the East Kaibab monocline.

Dutton (1880) thought of the Kaibab plateau as an uplifted rock mass bordered by an eastern and a western Kaibab fault that unite in the vicinity of Paria. Walcott (1890) also classed the Kaibab Plateau as essentially a fault block and expressed the view that the earth movements that produced the upwarp began in early Paleozoic time, ceased "in the later part of Paleozoic time", and then resumed their activities. In contrast with the views of the pioneer geologists recent surveys show that the Kaibab upwarp as exposed in central Kane County owes little if any of its height and attitude to faulting. The disconnected fractures along its eastern base, some of them with downthrows on the west, seem genetically related to the East Kaibab monocline. They have been effective chiefly in cutting out parts of the soft Triassic rocks. Along the western front of the upwarp most of the rare fractures record slips along joint planes where the dips of the strata are unusually steep.

In Utah the Kaibab upwarp has disturbed all the Permian and Triassic formations and the Jurassic (?) Glen Canyon group and probably the Upper Jurassic and Cretaceous beds that once extended across central Kane County but now lie outside of the region of upcurved rocks. Regional studies show a strong improbability that Tertiary rocks were involved. The upwarping is therefore believed to be pre-Tertiary and substantially contemporaneous with the movements that produced the East Kaibab monocline. It thus antedates the movements in the Paunsaugunt fault zone.

EAST KAIBAB MONOCLINE

Among the major flexures that have disturbed the sedimentary rocks in the Colorado plateau province the East Kaibab monocline holds high rank. It is about 150

miles long, records stratigraphic displacements of 2000 feet to more than 4500 feet, and though erosion has greatly reduced its height and otherwise modified its original form the structure persists as a prominent topographic feature visible at long distances and especially impressive in near-by views. The East Kaibab monocline is especially conspicuous between Shurtz Gorge and Catstairs Gorge, where it stands as a saw-toothed ridge—an outstanding scenic featured named by the pioneer settlers the Coxcomb. For a distance of about 8 miles south of Shurtz Gorge the narrow crest of the monocline stands about 1150 feet above the Paria River on the east and 800 feet above Robinson Creek on the west. Farther southwestward some of its higher parts have been removed by erosion, but their remnant-truncated strata are recognizable along West Clark Bench and the Paria Plateau until lost to view beneath the alluvium of House Rock Valley.

The eastern flank of the flexure dips eastward in conformity with the attitude of its component Jurassic strata which, in the Coxcomb, are inclined at angles of 20° to 40°, in places 60°, and before reaching the Paria River abruptly flatten; dips as high as 30° may change to less than 3° in a distance of 500 feet (Pl. 8). On this slope the younger rocks seem to be plastered against the core rock of Navajo sandstone, and the short swift-canyoned streams have cut them into rectangular and triangular segments which lean against the general slope like boxes and upturned flatirons. Unlike the eastern flank the western flank of the monocline is entirely out of accord with the attitude of the sedimentary rocks. Its steep slopes have been developed by truncating the Navajo sandstone and the Chinle formation, which dip in an opposite direction, and hence present a sequence of cliffs whose heights measure the thickness of the harder beds.

The structural displacement along the East Kaibab monocline in central Kane County averages about 4500 feet—an estimated minimum of 3600 feet, and a maximum of 5000 feet. Across House Rock Valley within 3 or 4 miles one may pass from the top of the Kaibab limestone to the top of the Navajo sandstone and in places to the Dakota sandstone. The Navajo sandstone in the Coxcomb and the Straight Cliffs sandstone (Cretaceous) in the Kaiparowits Plateau are approximately concordant.

The monoclinal flexure has involved all the Permian, Triassic, Jurassic, and Cretaceous rocks represented in southern Utah and adjoining parts of Arizona, and, from south to north, in consequence of erosion guided by regionally northward dips, successively younger formations appear at the surface. Along the western flank of the structure consequent and subsequent streams have excavated runways in the relatively soft Triassic rocks of House Rock Valley, and along the eastern flank the subsequent Cottonwood Creek has developed a broad floor—the "race track"—in the unresistant Upper Jurassic rocks, 100 to 400 feet below the Dakota sandstone in the bordering hogbacks.

Throughout its course the East Kaibab monocline has been developed by folding, unaccompanied by large-scale faulting. On its eastern flank the abruptly downturned strata appear to be unbroken. Also along its western base the sequence of strata is generally complete, but in House Rock Valley, where local faults have cut out parts of the tilted Triassic beds, a more or less continuous, narrow belt of fractured rock may lie beneath the alluvium. In the walls of Shurtz Gorge and Catstairs

Gorge, and generally along the Coxcomb, the thick-bedded upper Chinle formation and especially the massive Navajo sandstone are traversed by prominent joint cracks and fracture belts, and here and there the rocks have been displaced by small-scale slipping and shearing.

In places along their courses the Kaibab monocline and the Kaibab upwarp are closely associated. In Arizona they are so completely merged that the monocline is not clearly represented in the topography; it merely defines the eastern border of the Kaibab and Coconino plateaus (Pl. 9). Beginning near the Utah-Arizona boundary the axes of the two structures diverge, and the monocline retains its characteristic features for fully 20 miles beyond the poorly defined north end of the upwarp. In places where the two flexures are separate but close together the establishment of their boundaries is guess work. Thus across upper House Rock Valley and up the west flank of the monocline the dip of the strata progressively steepens eastward, but the sequence of the Permain, Triassic, and Jurassic beds is substantially unbroken. Farther north, however, dips of tilted beds in the monoclinal mass decrease rapidly at its border and within a short distance regain their original attitude.

Dutton (1880) described the "Eastern Kaibab fault" (substantially the East Kaibab monocline) as a continuous structure that, beginning in the vicinity of the San Francisco Mountain, extends northward across Arizona and Utah to the Wasatch Plateau. He speaks of the "Kaibab fault" and the Paunsaugunt fault as "branches of one displacement".

Walcott (1890) expressed the belief that the movement along the East Kaibab monocline:

> "began in the region of the Grand Canyon as a pre-Cambrian fault. . . . A period of rest then ensued that was broken, in the later part of Paleozoic time, by the formation of an eastward facing monoclinal fold of a few hundred feet. . . . From the close of the Paleozoic to the Middle Tertiary there is no known evidence of any movement along the line of the East Kaibab displacement. The intervening time appears to have been one of slow subsidence and quiet deposition of sediments. From the evidence given by Captain Dutton (U. S. Geol. Survey Mon. 2, p. 70, 1882), it is scarcely to be doubted that the later displacements are of Tertiary age and that the movement continued to a comparatively recent date."

More recent studies (Gregory and Moore, 1931; Gregory, in press, b; Babenroth and Strahler, 1945) serve to modify the conclusions reached by Dutton and his coworkers. They show that as a clearly defined tectonic feature the East Kaibab monocline extends from the Coconino Plateau northward to the Kaiparowits Plateau, beyond which its expression is increasingly indistinct, and that the Paunsaugunt fault is a major zone of displacement and differs from the monocline in origin, age, alinement, and as a controlling factor in the development of the topography. Near Kaiparowits Peak ("Canaan Mountain") the steeply inclined strata in the monocline, including the youngest Cretaceous, have been beveled by erosion and overlain by the essentially horizontal conglomerates and limestones of the Tertiary Wasatch formation. Thus, movement along the great fold probably ceased at or near the end of Cretaceous time, and the erosion represented by the pre-Wasatch unconformity dates from early Eocene or very late Cretaceous time.

OUTLINE OF PHYSIOGRAPHIC HISTORY

The cliffs, canyons, high-lying terraces, and low-lying flat lands that characterize the topography of central Kane County record stages in the physiographic history

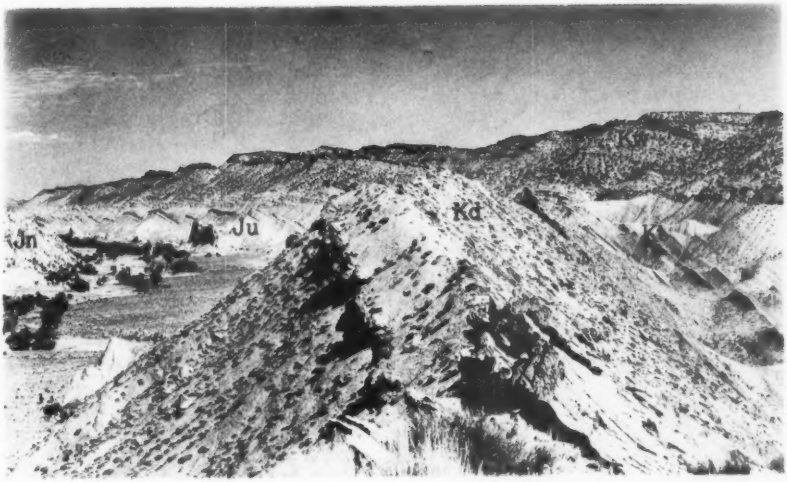


FIGURE 1. LOOKING NORTH FROM PARIA RIVER UP COTTONWOOD CREEK
Eastward-tilted rocks are Navajo sandstone (Jn), upper Jurassic (Ju), Dakota sandstone (Kd), Tropic shales (Kt), and Wahweap sandstone (Kw).

FIGURE 2. LOOKING DOWN PARIA RIVER FROM MOUTH OF SHURTZ GORGE
Navajo sandstone (right sky line) overlain in turn by upper Jurassic and Cretaceous rocks. Flat surface (middle distance) bevels upturned strata.

FIGURE 1. LOOKING DOWN PARIA RIVER
Navajo sandstone (sky line) and upper Jurassic at abandoned village of Adairville. Flat-lying Jurassic strata of East and West Clark Bench.

FIGURE 2. LOOKING SOUTHWEST FROM WEST CLARK BENCH ACROSS HOUSE ROCK VALLEY TO CREST OF KAIBAB UPWARP (RIGHT SKY LINE)
Topographic features in middle distance are erosion remnants of the East Kaibab monocline.

of the entire Colorado plateau province. Field studies indicate that the rocks exposed on the Kaibab Plateau, in Kimball Valley, in the Vermilion Cliffs, the White Cliffs, and the Pink Cliffs farther north were deposited in succession near sea level, that they once extended across southern Utah and far southward into Arizona, and that with little modification in attitude they were uplifted en masse. Thus the topmost rock (Tertiary) was brought to heights exceeding 8000 feet. There the rocks presented a relatively flat surface similar in form and attitude to the top of the Paunsaugunt Plateau. Since the lands were uplifted to their maximum height their physiographic history is chiefly the record of reduction of high lands to lower lands by stream abrasion, weathering, and transporting the resultant rock waste. It seems reasonable to assume that the ancestral drainage system in central Kane County was developed on lands far above sea level and consisted of a few streams that flowed northward in accord with the regional inclination of the sedimentary beds. After the Colorado became established as the master line of drainage for the plateau country its tributaries lengthened, and in consequence of headward erosion the divide between the north-flowing and south-flowing streams that once stood near the Colorado has retreated to the rim of the High Plateaus. From this clearly defined drainage parting the headwaters of streams that cross Kane County descend precipitously through innumerable narrow deep gullies, in strong contrast with the slowly moving streams and widely flaring valleys on the Paunsaugunt and Aquarius plateaus, which retain the pattern of an ancient drainage system. Regional uplift gave the south-flowing streams the strength necessary to dig deep runways and to wear down the rock on intercanyon areas. Though the task of reducing the rugged highlands to a plain of low relief is far from complete, these streams have stripped from central Kane County stratified rocks more than a mile thick. The many-branched Paria River and Johnson Creek have been powerful enough to make their way southward across strata that dip northward; they have even kept their courses over the masses of upturned resistant rocks encountered in their deepened channels. Without substantial change in their probable original alinement the Paria River leaves a broad valley and plunges through the East Kaibab monocline, and its chief western tributaries, Sand and Kaibab creeks, have gouged courses across both the monocline and the Kaibab upwarp. These great folds, which were concealed by flat-lying rocks when streams first crossed their sites, are now prominently exposed, and the streams that cross them in Shurtz and Catstairs gorges and in Sand and Kaibab gulches seem completely out of place. Thus the natural course for the lower Paria River and for the streams that cross or flow down the steep sides of the Coxcomb and the Kaibab Plateau appears to be House Rock Valley, which lies far below the surrounding highlands and slopes toward the Colorado River. At the present time only House Rock Creek that drains the southern part of the valley (in Arizona) flows directly to its master stream. Farther north the topographically continuous House Rock Valley is occupied by short, ephemeral, consequent, and subsequent streams that head in low divides where erosion is rapid. Although these streams are now tributaries to Sand and Kaibab creeks which cross the valley, no great amount of erosion would be required to erase the divides and thus convert the gulches of various trends into a continuous south-flowing channel, suitable for carrying the run-off from House Rock Valley and large adjacent areas.

Among the effective processes concerned with remodeling the Kane County landscape, downcutting of the drainage channels by streams has been dominant but not uniform in rate. The present topography reveals wide-scale changes in stream habit, and doubtless throughout their lives the streams oftentimes experienced considerable change in erosive power for which the records have been destroyed. Many canyons and open valleys present evidence of alternating periods of downcutting and widening, of dominant aggradation and degradation. Pauses in the generally rapid downward erosion are recorded in the valley profile. In places the floor of a moderately wide canyon is trenched by a narrow rock-walled gorge,—a canyon within a canyon—and elsewhere the remnants of old peneplanes are parts of the valley walls. At the mouth of Shurtz Gorge an erosion surface has been developed by truncating tilted strata, and on West Clark Bench remnants of a similar surface, here protected from erosion by slab gravels, are features of high mesas (Pl. 7).

After the canyons had been sunk in rock to their maximum depth and central Kane County had attained much of its present topographic ruggedness, downcutting seems to have ceased; the valley floors were covered by alluvium 10 to more than 50 feet thick, and on intervalley areas erosion and transportation of rock waste reached its minimum, thus facilitating the accumulation of products of weathering and the formation of soil. The alluvial banks of present streams and remnant terraces show that in consequence of valley filling the streams were graded at low inclination—in places so low that standing bodies of water were permitted to form. The ponds in Lake Canyon and Kitchen Valley have this origin.

The period of dominant downcutting (the canyon epicycle) was followed by a period of alluvial deposition (the inner canyon epicycle) which as judged from artifacts dates from the middle of the seventeenth century, and in turn by a period of rapid erosion (the terrace epicycle), which began in the latter part of the nineteenth century and has yet not ended. At present in southern Kane County erosion is vigorous. From the high escarpments and the faces of low ridges and mesas, swiftly flowing ephemeral rills are now carrying away the products of rock disintegration about as fast as they are formed, and their effectiveness is increased by mass movements of loosened bedrock exemplified by the huge landslide backed against the Coxcomb and the Vermilion Cliffs at Mine Gulch. Consequently the accumulations of talus are relatively small; many outer canyon walls, escarpments, and steep slopes present only bare rock. Furthermore most streams at their headwaters and at other places where their beds are steeply inclined are scouring bedrock and keeping their channels clear of extraneous debris and generally along their course are deepening their runways and digging out and transporting enormous quantities of rock waste deposited during a previous cycle (Pl. 7, fig. 3). The destruction of the alluvial fill is particularly rapid, in places and at times, spectacular. In pioneer days and as late as 1890 upper Kitchen Canyon was a region of swamps, ponds, and grassy meadows, famous for its choice forage. It is now crossed by a trench about 10 feet wide and 70 feet deep and by many smaller trenches. Likewise for many years the floor of Park Wash was an undissected surface of alluvium coated by grass and palatable herbage, the route of a wagon road from Kitchen Corral to Five Pines. About 1895 the shallow, narrow streamway began to deepen and since that time has continued to cut downward and sideways into alluvium 10 to 30 feet thick, destroying grazing

land and farm land in the main wash, and stripping the branch washes of their soil. In August 1943 a turbulent stream produced by a single heavy shower was observed to dig a trench 30 feet wide, 18 feet deep, and 800 feet long. Canyons in which the alluvial fill is in process of destruction have a cross profile characteristic of southern Utah topography. From an inner vertically walled gorge cut 20 to 80 feet into sand and gravel the valley floor extends as terraces to the base of the rock cliffs that wall the outer canyon. This recent trenching and terracing of the alluvial valley fill is of prime importance to the stockmen and farmers in central Kane County. It has resulted in the destruction of some of the best meadow land, lowered the streams to levels where obtaining water for irrigation is almost impossible, and caused the relocation of buildings and roads. Largely for these reasons the settlements at House Rock, Adairville, Paria, and Johnson City were abandoned.

REFERENCES CITED

Babenroth, D. L., and Strahler, A. N. (1945) *Geormorphology and structure of the East Kaibab monocline, Arizona and Utah*, Geol. Soc. Am., Bull., vol. 56, p. 107–150.

Baker, A. A., Dane, C. H., and Reeside, J. B., Jr. (1936) *Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado*, U. S. Geol. Survey, Prof. Paper 183.

Branson, E. B. (1927) *Triassic, Jurassic "red beds" of the Rocky Mountain region*, Jour. Geol., vol. 35, p. 607–630.

Darton, N. H. (1925) *A resume of Arizona geology*, Univ. Ariz., Bull. 119.

Dutton, C. E. (1880) *Report on the geology of the High Plateaus of Utah*, U. S. Geog. Geol. Survey Rocky Mtn. Region (Powell) 307 pages.

Gilbert, G. K. (1875) *Report on the geology of portions of Nevada, Utah, California and Arizona*, U. S. Geog. Geol. Survey W. 100th Mer., vol. 3, p. 160.

Goldman, M. I., and Spencer, A. C. (1941) *Correlation of Cross' La Plata sandstone, southwestern Colorado*, Am. Assoc. Petrol. Geol., Bull., vol. 25.

Gregory, H. E. (in press, a) *The Zion Park region, Utah*, U. S. Geol. Survey.

——— (in press, b) *The Paunsaugunt region, Utah*, U. S. Geol. Survey.

——— (1917) *The Navajo Country*, U. S. Geol. Survey, Prof. Paper 93.

——— and Anderson, J. C. (1939) *Geographic and geologic sketch of the Capital Reef National Monument*, Geol. Soc. Am., Bull., vol. 50, p. 1845.

——— and Moore, R. C. (1931) *The Kaiparowits region, Utah*, U. S. Geol. Survey, Prof. Paper 164.

Howell, E. E. (1875) *Report on the geology of portions of Utah, Nevada, Arizona and New Mexico*, U. S. Geog. Geol. Survey W. 100th Mer., vol. 3, p. 227–301.

Huntington, Ellsworth, and Goldthwait, J. M. (1904) *The Hurricane fault in the Toquerville district, Utah*, Harvard Coll., Mus. Comp. Zool., vol. 42.

Lawson, A. C. (1913) *The gold in the Shinarump at Paria*, Econ. Geol., vol. 8, p. 434–448.

Noble, L. F. (1928) *A section of the Kaibab limestone in Kaibab Gulch, Utah*, U. S. Geol. Survey, Prof. Paper 150, p. 4–60.

Reeside, J. B. Jr. (1943) Letter to the Chief Geologist, U. S. Geol. Survey, December 10.

——— (1945) Letter to the Chief Geologist, U. S. Geol. Survey, January 13.

———, and Bassler, Harvey (1922) *Stratigraphic sections in southwestern Utah and northwestern Arizona*, U. S. Geol. Survey, Prof. Paper 129, p. 53–73.

Stokes, W. L. (1944) *Morrison and related formations in and adjacent to the Colorado Plateau*, Geol. Soc. Am., Bull., vol. 55, p. 951–992.

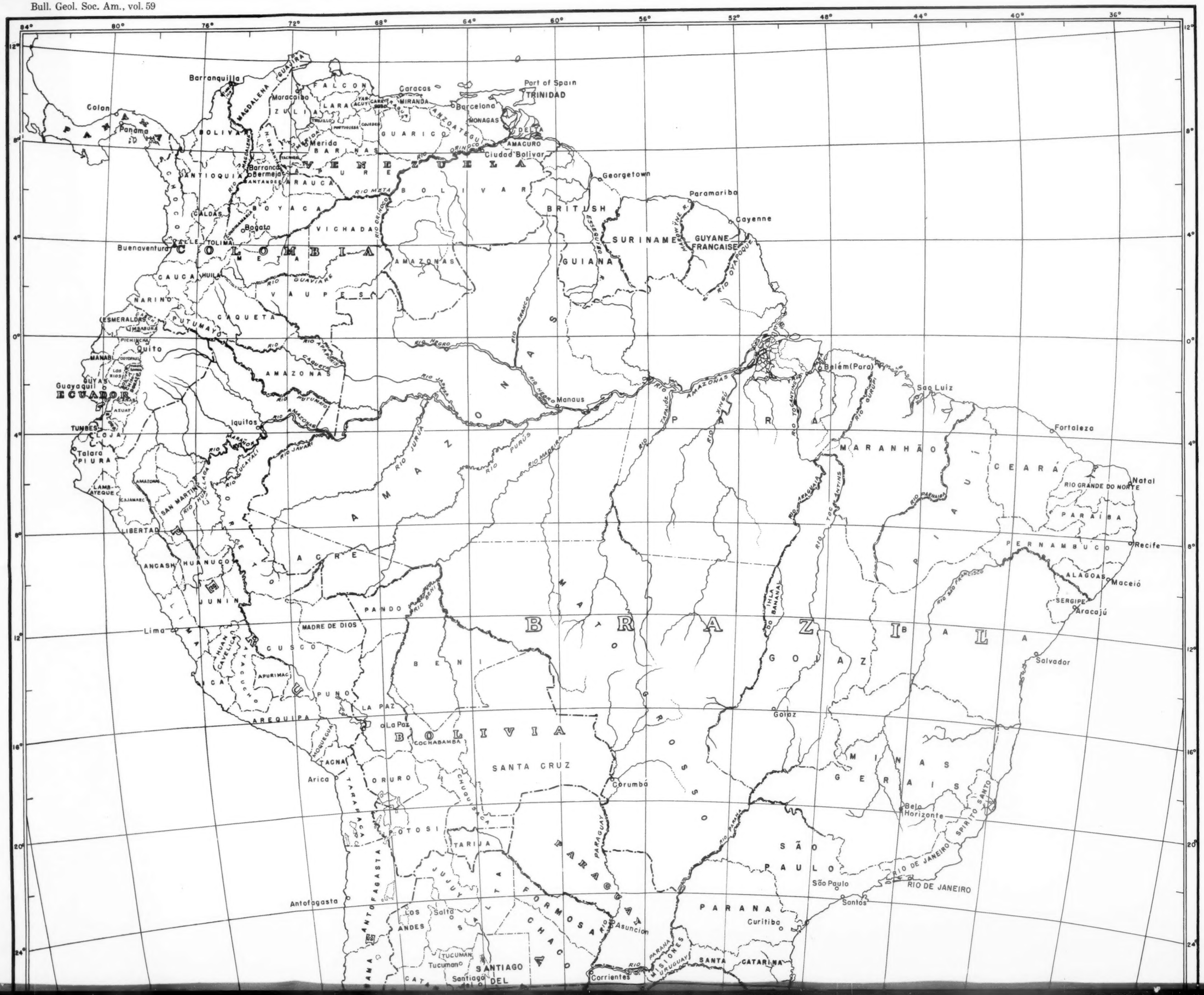
Walcott, C. D. (1890) *Study of a line of displacement in the Grand Canyon of the Colorado, northern Arizona*, Geol. Soc. Am., Bull., vol. 1, p. 63–64.

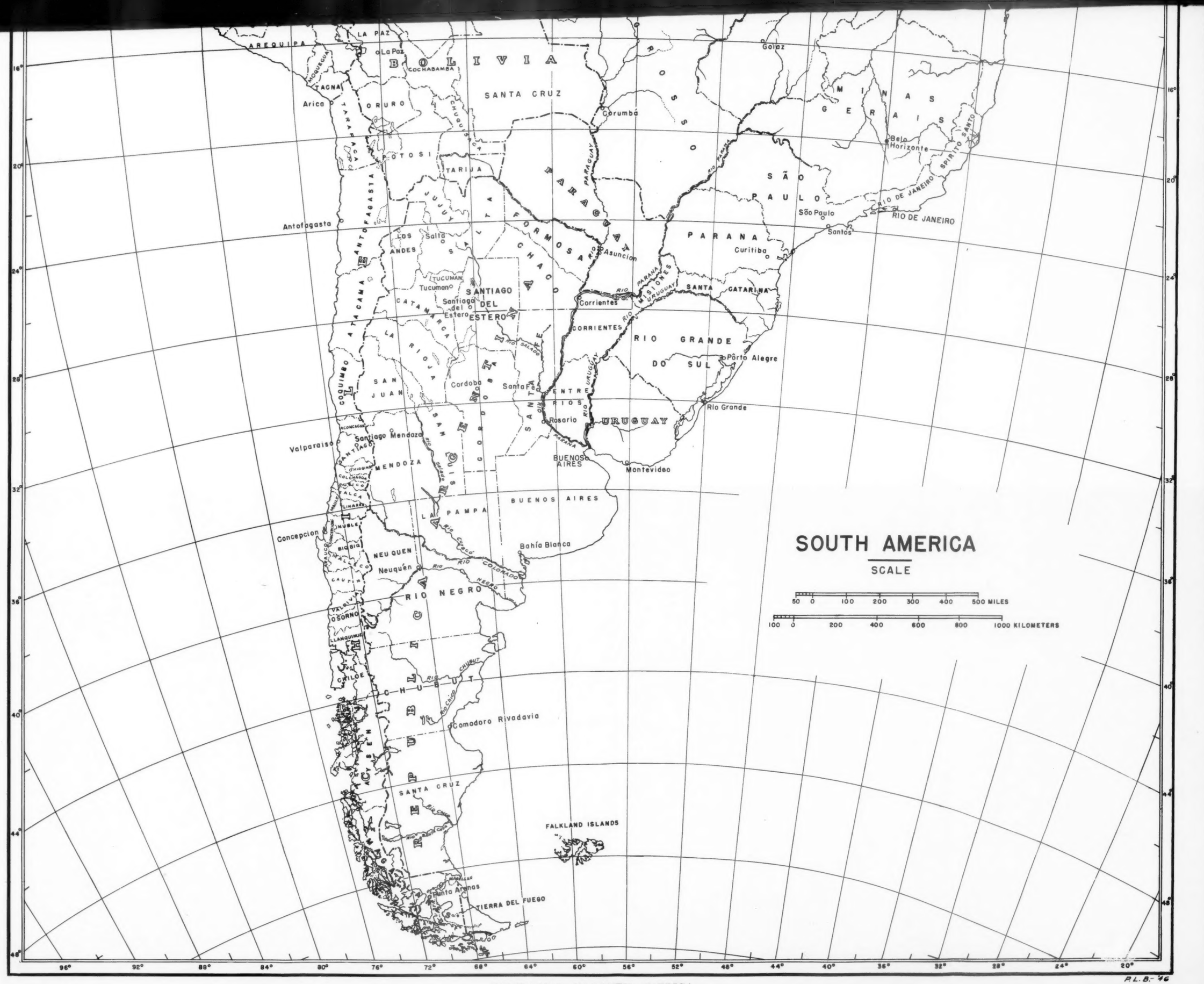
Wheeler, G. M. (1889) *Geographical report*, U. S. Geog. and Geol. Survey W. 100th Mer.

B.P. Bishop Museum, Honolulu, Hawaii

Manuscript Received by the Secretary of the Society, May 12, 1946

UNIVERSITY OF CALIFORNIA


84°
80°
76°
72°
68°
64°
60°
56°
52°
48°
44°
40°
36°
12°
8°
4°
0°
4°
8°
12°
16°
20°
24°
Barranquilla
Colon
Panama
Maracaibo
Caracas
Port of Spain
TRINIDAD
Barcelona
Merida
Barranca Bermejas
Bogata
Buenaventura
Quito
Guayaquil
ECUADOR
Iquitos
Talara
PIURA
Lima
Arica
Antofagasta
Salta
Tucuman
Santiago del Estero
Asuncion
Corrientes
Ciudad Bolivar
Georgetown
Paramariba
Cayenne
Manaus
Belém (Para)
São Luiz
Fortaleza
Natal
Recife
Maceió
Aracajú
Salvador
Goiaz
Corumbá
Belo Horizonte
São Paulo
Santos
RIO DE JANEIRO
Curitiba
COLOMBIA
VENEZUELA
BRITISH GUIANA
SURINAME
GUYANE FRANCAISE
BOLIVIA
PARAGUAY
BRAZIL
AMAZONAS
PARA
MARANHÃO
CEARÁ
RIO GRANDE DO NORTE
PARAIBA
PERNAMBUCO
ALAGOAS
SERGIPE
MINAS GERAIS
SÃO PAULO
PARANA
SANTA CATARINA
RIO DE JANEIRO
ESPIRITO SANTO
GOIAZ
MATTO GROSSO
ACRE
PANDO
BENI
SANTA CRUZ
CHACO
FORMOSA
MISIONES
ANDES
LA PAZ
COCHABAMBA
ORURO
POTOSI
TARIJA
JUJUY
TUCUMAN
SANTIAGO DEL ESTERO
CATAMARCA
TACNA
AREQUIPA
PUNO
CUSCO
APURIMAC
HUANCAVELICA
JUNIN
ANCASH
HUANUCO
LIBERTAD
LAMBAYEQUE
CAJAMARCA
AMAZONAS
LORETO
TUMBES
LOJA
AZUAY
CAÑAR
GUAYAS
LOS RIOS
MANABI
COTOPAXI
PICHINCHA
IMBABURA
ESMERALDAS
NARIÑO
PUTUMAYO
CAQUETA
CAUCA
HUILA
VALLE
TOLIMA
CALDAS
ANTIOQUIA
CHOCO
BOYACA
CUNDINAMARCA
SANTANDER
ARAUCA
CASANARE
VICHADA
VAUPES
GUAINIA
AMAZONAS
BOLIVAR
GUARICO
ANZOATEGUI
MONAGAS
DELTA AMACURO
BARINAS
MERIDA
TACHIRA
TRUJILLO
PORTUGUESA
COJEDES
YARACUY
CARABOBO
ARAGUA
MIRANDA
FALCON
LARA
ZULIA
GUAJIRA
MAGDALENA
RIO ORINOCO
RIO META
RIO ORINOCO
RIO CAQUETA
RIO PUTUMAYO
RIO NEGRO
RIO JAPURA
RIO JAVARI
RIO AMAZONAS
RIO YAPURA
RIO APAPORIS
RIO GUAVIARE
RIO ERANCO
RIO ESSEQUIBO
RIO OYAPOQUE
RIO MARONI
RIO TAPAJOS
RIO XINGÚ
RIO TOCANTINS
RIO ARAGUAYA
RIO PARNAIBA
RIO GURUPI
RIO SÃO FRANCISCO
RIO PARANA
RIO PARAGUAY
RIO MADEIRA
RIO PURUS
RIO JURUA
RIO ACRE
RIO BENI
RIO MAMORE
RIO GUAPORE
RIO PILCOMAYO
RIO BERMEJO
RIO SAN MARTIN
RIO HUALLAGA
RIO UCAYALI
RIO MARAÑON
RIO PASTAZA
RIO NAPO
RIO SANTIAGO
RIO MORONA
RIO ZARUMILLA
RIO CAUCA
RIO MAGDALENA
RIO SINU
RIO ATRATO
RIO SAN JUAN
RIO CHAGRES
RIO CHAMA
RIO SUCIO
RIO CATATUMBO
RIO ZULIA
RIO TACHIRA
RIO ARAUCA
RIO CUCUTA
RIO ARIPORO
RIO CAPANAPARO
RIO CARONI
RIO CUCHIVERO
RIO CARRAO
RIO CARONI
RIO PARU
RIO JARI
RIO ARAGUARI
RIO TARTARUGALZINHO
RIO GURUPI
RIO MEARIM
RIO ITAPECURU
RIO PARNAIBA
RIO GRANDE
RIO PARDO
RIO PARANAHYBA
RIO SÃO FRANCISCO
RIO DOCE
RIO PARAHYBA
RIO PARAHYBUNA
RIO PARANAPANEMA
RIO IGUASSU
RIO URUGUAY
RIO PARANA
RIO PILCOMAYO
RIO BERMEJO
RIO SALADO
RIO DULCE
RIO SALADO
RIO PARAGUAY
RIO TAQUARY
RIO APA
RIO MIRANDA
RIO NABILEQUE
RIO ITENEZ
RIO GUAPORE
RIO MADEIRA
RIO TAPAJOS
RIO XINGÚ
RIO TOCANTINS
RIO ARAGUAYA
RIO PARNAIBA
RIO GURUPI
RIO SÃO FRANCISCO
RIO PARANA
RIO PARAGUAY
RIO MADEIRA
RIO PURUS
RIO JURUA
RIO ACRE
RIO BENI
RIO MAMORE
RIO GUAPORE



INDEX MAP OF SOUTH AMERICA

Abstract
Introduc
Continen
Algonkia
Cambro-
Silurian.
Devonia
Mississip
Upper C
Triassic.
Lower a
Tithonia
Aptian-A
Late Cer
Late Sen
Eocene.
Oligocen
Middle
Upper M
Pliocene
Selected

Figure
1. Sed

Plate
1. Ind
2–16.

The
Attenti
framew

The
pictured
sedimen
gression
caused

The
features

1. La

2. Up
mentatio

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 59, PP. 249-282, 16 PLS., 1 FIG. MARCH 1948

PALEOGEOGRAPHY OF SOUTH AMERICA

BY L. G. WEEKS

CONTENTS

	Page
Abstract	249
Introduction	251
Continental framework	251
Algonkian	253
Cambro-Ordovician	254
Silurian	255
Devonian	256
Mississippian	256
Upper Carboniferous-Permian	257
Triassic	258
Lower and Middle Jurassic	259
Tithonian-Neocomian	261
Aptian-Albian-Lower Cenomanian	262
Late Cenomanian-Turonian-Lower Senonian	262
Late Senonian-Paleocene	263
Eocene	264
Oligocene-Early Miocene	265
Middle Miocene	265
Upper Miocene	266
Pliocene	266
Selected bibliography	267

ILLUSTRATIONS

Figure	Page
1. Sedimentary basins, Western Hemisphere	252

Plate	Facing page
1. Index map of South America	249
2-16. Paleogeographic maps	(At end of paper)

ABSTRACT

The major features of the geologic framework of the continent are outlined. Attention is called throughout the paper to the many similarities in the continental framework and geologic history of South America with those of North America.

The change in paleogeography and facies from Cambrian to Pliocene inclusive is pictured on 15 paleogeographic facies maps (Pls. 2–16) selected to show the principal sedimentary overlaps. Intervening changes and conditions, the progress of transgressions, and the fundamental transitions in the architecture of the continent that caused or conditioned the paleogeographic and facies changes are briefly reviewed.

The major events as interpreted from the stratigraphy, structure, and other features of the geology are:

1. Late Proterozoic diastrophism.

2. Upper Cambrian marine transgression and wide-spread late Cambrian-early Ordovician sedimentation, with less extensive deposits of middle and later Ordovician and early Silurian time.

3. Main Caledonian orogenies of late Ordovician to Silurian, and a general withdrawal of the seas during much of the Silurian. The best-developed Silurian seaways, as in North America, are apparently in the eastern part of the continent.

4. Marine advance in late Silurian and early Devonian. An extensive development of Lower Devonian sediments, which embrace the major part of the Devonian sediments of South America. However, a middle Devonian marine invasion spread through the Colombia-Venezuela and Amazon troughs and southward down the Cordilleran trough at least as far as 20° S. Lat.

5. Upper Devonian sediments are unknown in South America. Mississippian marine sediments occur in the West-Central Argentine embayment and at least locally in the Colombian seaway; and they may yet be found in the Cordilleran trough of Peru and Bolivia, *etc.*, where continental beds of Mississippian and probably also Pennsylvanian ages occur.

6. Mid-Pennsylvanian marine sediments are known locally in the Cordilleran trough, but the first major marine advance following the Devonian began in the late Pennsylvanian and persisted through the early Permian. It covered approximately the same areas that were occupied by Devonian seas. Glaciation occurred south of about 20° S. Lat., and its deposits are interfingered with both marine and continental sediments in the southern areas. Less extensive, mainly continental sedimentation of later, possibly mid-Permian age, locally carrying glacial deposits in the south, rest disconformably on early Permian.

7. Marine sediments of Upper Permian and Lower and Middle Triassic age are not recognized on the continent. Some plant- and coal-bearing beds in Peru are thought to be mid-Triassic.

8. The sea advanced from the west during the Upper Triassic into the basins occupied by Permian sedimentation. The marine sediments interfinger with and change to a continental facies toward the margins of the advance. These continental clastics overlap beyond those of the Permian in many places.

9. A new pattern of geosynclines, whose formation began along the belt of the present Cordillera in the Triassic, is outlined by Jurassic sediments whose main seas existed in the Lias, Bajocian, and Callovian ages. Barred basins developed in these geosynclines. These were sufficiently closed to deposit salt and anhydrite in the Oxfordian stage.

10. A readvance of the sea in the late Jurassic, Tithonian, spread sediments of Tithonian and early Cretaceous Neocomian stages through somewhat more extended areas of the western geosynclines, opening southward through Tierra del Fuego, and also extending for the first time across the northern part of the continent.

11. In the Aptian-Albian-Lower Cenomanian (Comanche) ages of the Cretaceous the Cordilleran seaways enlarged in the northern and northwestern areas and receded toward the new southern Patagonian embayment. A marine embayment appeared for the first time in the Bahia area of the Brazilian coast.

12. A withdrawal of the seas in the Cenomanian was followed in late Cenomanian and Turonian time by a wide marine advance over the areas of Aptian to early Cenomanian sedimentation. Deposits of this sea are most prominently developed in the Turonian and lower Senonian stages. As a preliminary to the uplift of the Andes, the overall slope of the continental platform, which had been largely westerly during the Paleozoic and Lower Mesozoic, began to take a more level stand. As a consequence extensive, largely fresh-water lakes spread over the interior of the continent during the Upper Cretaceous.

13. Two or more relatively minor to locally more severe movements affected the continent in the late Cretaceous. The first caused a retreat of the sea in the Upper Senonian. In many parts of South America, as in other parts of the world, a well-defined hiatus separates the Tertiary from the Cretaceous. However, the seas advanced into the deeper parts of the troughs and embayments to deposit sediments of late Senonian to Paleocene stages.

14. The first major Andean orogenic movement of the Tertiary occurred in post-Paleocene, early Eocene time. A marine advance followed which spread widely in the middle Eocene, and there were further lesser retreats and prominent readvances in the upper Eocene.

15. A second major Andean movement had its climax in early Oligocene. This was followed by sea advances of middle Oligocene to early Miocene time.

16. The Oligo-Miocene deposits spread headward and inland and continued upward through the Middle Miocene into brackish and still more continental facies, while they remained marine in character in more restricted episeas of the continental margins.

17. Upper Miocene time brought a further general retreat of seas and a drying-up of interior areas preliminary to a third major Andean orogenic-epeirogenic movement in late Miocene.

18. The seas readvanced into certain local embayments and marginal areas in the Pliocene.

19. Continental deposition continued along the Andean front in the Pleistocene as the fourth major Andean movement raised the Cordilleras to approximately their present conformation. Glaciation developed in the higher mountains and was general over southern Patagonia.

20. Taphrogenic breakdown and general subsidence of continental border areas and belts, which began in the Mesozoic, became more pronounced in the late Tertiary and Quaternary.

INTRODUCTION

Our understanding of the geology of the earth or any part of it is constantly undergoing change. This condition of change and growth as new facts come to light is one that is common to all sciences. Every geologic map is, in effect, a progress map, imperfect and vulnerable. However, there is no area of the earth, large or small, and no problem in geology that cannot be understood better when it can be visualized against a broader background. Paleogeographic maps of South America for 20 principal deposition overlaps or units of sedimentation from the Cambrian to the Pleistocene were prepared by the writer 7 years ago in the course of developing similar broad regional studies of the earth. The accompanying maps incorporate various subsequent revisions and no doubt will require many more. With few exceptions (certain ages and areas of the lower Paleozoic in particular), future revisions will be concerned more with refinements of detail and of facies distribution than with the existence and general outlines of the major seaways and embayments.

The compilations are based on 22 years of growing familiarity with the geology of South America, about 15 years of which were spent in field study of many parts of the continent from the Caribbean on the north to Tierra del Fuego on the south. In addition to this first-hand source of information the writer is greatly indebted to his colleagues in the field and to many sources of published information. A selected bibliography of several hundred papers, books, and other publications is appended. No doubt other good papers exist that have escaped the writer's attention.

The writer is much indebted to paleontologists, particularly to those who are also stratigraphers and who are able to rationalize their findings by fitting them into the broad regional picture of stratigraphic similarities and facies changes and the fourth dimension—geologic time.

In discussing a subject as vast as that here involved within the limits of space and time available, only the barest outline can be given. The paleogeographic maps shown are selected to picture the principal units of sedimentary overlap or "layers of geology". These chapters are fitted into the geologic story of the continent after a brief look at the continental framework with the aid of Figure 1, which shows the present structural (in contrast to original sedimentary) basin areas of the two Americas.

CONTINENTAL FRAMEWORK

The geologic framework of the continent of South America bears many similarities to that of North America. Chief of these are:

(1) The right-angle triangular shape.

(2) The great central stable shield or continental nucleus—Canadian shield in North America and Brazilian shield in South America, each covering a vast area in the northeast-central part of the continent.

FIGURE 1.—*Sedimentary basins, Western Hemisphere*

(3) The long mobile belt, consisting of asymmetric geosynclinal troughs and borderlands, which fringed the forelands of the stable shield areas on the west throughout most of geologic history and which, through a series of orogenies, developed into the lengthy Cordilleras of today.

(4) The development of mobile belts, now marked by the southwest-trending so-called Brazilides of eastern Brazil and the middle Argentine ranges, that are broadly similar in respect to position, age, and trend, although on a very much lesser scale of development, to the Appalachian-Ouachita-Llanoria belts in North America.

(5) The remarkable similarity of the West Indian arc, connecting North America and South America through southern Mexico, northern Central America, the Greater and Lesser Antilles, and the northern Trinidad and Venezuelan coast ranges, with the southern arc which connects Antarctica with South America through Tierra del

Fuego, Burdwood, South Georgia, South Sandwich, South Orkneys, South Shetlands, and the Antarctides. (Evidently the connection between the two continents through Central America is not that of the ordinary tectonic mobile belt of the crust. The tectonic mobile belt connection clearly follows the arc of the Antilles into its Andean continuation in South America. The more direct connection through Central America is rather clearly that of a volcanic bridge across the easterly embaying Pacific-Caribbean plate. The basic lavas forming that bridge and the similar lavas comprising part of the foundation of the Antilles rose incidental to the collapse of the Pacific-Caribbean areas. This collapse and the extravasation of the basic volcanic lavas to form the bridge occurred since the Cretaceous, just as the thousands of Tertiary-Quaternary volcanic islands and island ridges throughout the Pacific region rose during the same period which, on balance, was one of subsidence of the ocean plate.)

(6) The similar spread of seas over the forelands and interior shield areas at similar periods from the major troughs and seaways that lay in the main on the west and southwest. Seas entered also at certain periods on both continents from the northeast and/or northwest.

(7) The similar changes in general pattern of the paleogeography (shown on the accompanying maps in the case of South America) from that of the Paleozoic to that following the Triassic. On both continents new Mesozoic-Tertiary geosynclines opened along the backs or hinterlands of the Paleozoic mobile belts, extending from beyond Japan through southern Alaska and through western North America and South America.

(8) The high plateaulike widening and westward bulge in the region of the middle Cordilleras on both continents.

(9) The marine overlaps of Cretaceous-Tertiary age from the east and southeast on both continents. These overlaps developed with the uplift of the Cordilleras, which brought about a change in the overall tilt or surface slope of both continental blocks from the westerly one that was generally prevalent prior to the Cretaceous to an easterly or southeasterly slope subsequent thereto.

(10) The subsidence, largely during the period from late Cretaceous to the present, of the hinterland belts of the Cordilleras beneath the waters of the Pacific along the coasts of both continents.

Numerous other similarities exist, many of which will be mentioned. However, there are differences of interest. One is the fact that, with few exceptions, the extent and the depth of epeiric seas was somewhat less in South America than in North America. Likewise marine conditions in South America were less prevalent or continuous, and there was a lesser volume of sediments left by the seas than in the northern continent. Another difference is that, relative to North America, there is a rather low representation of carbonate rocks in the basin sediments.

ALGONKIAN

Deposits of the Algonkian or late pre-Cambrian are difficult to differentiate in many cases. Sediments of many ages up to even Triassic, Jurassic, and Cretaceous have been called pre-Cambrian at one time or another. Usually considered a part

of the Algonkian are a series of highly metamorphosed sediments, including huge deposits of high-grade iron ore, deposited in an ancient north-northeast trending geosyncline in eastern Brazil. Other iron-ore deposits occur in Venezuela south of the Orinoco. These occurrences recall that of the Lake Superior iron ores of similar age. Southward along the same trend in Brazil and Uruguay, in northern Paraguay, in southwestern Matto Grosso, and in the Andean belt of northern Argentina, Peru, and Bolivia, there occur old metamorphics which have been considered as pre-Cambrian but part of which may very well be younger. Other local occurrences, particularly in southern Brazil and Uruguay, sometimes placed in the early Paleozoic, fit more logically in the late pre-Cambrian.

CAMBRO-ORDOVICIAN

As in North America the widest extent of the Cambrian seas was in the upper or late Cambrian. In fact, no lower Cambrian has been identified in South America. Uppermost Cambrian and/or lowermost Ordovician marine sediments are known in the Macarena and neighboring parts of south-central Colombia. Ordovician is present in the Merida range of western Venezuela, at Puerto Berrio in the Magdalena valley of Colombia, and seems to be also represented at other places in northern Colombia. An Ordovician age is probably represented in the early Paleozoic sediments of southern Ecuador.

Middle and, particularly, Upper Cambrian marine sediments are known along the eastern Cordillera of Bolivia. This marine invasion transgressed southward into northern Argentina where it embayed in a less marine facies. Transgression continued in the Ordovician in the Cordilleran and pre-Cordilleran belt of Argentina, Bolivia, and Peru (Pl. 2).

Various marine advances and retreats are indicated, but the principal Ordovician occurrences are Lower and Middle Ordovician in age. Shales, largely graptolitic, change to a more sandy facies southward; farther south, in the somewhat detached San Juan-Mendoza area of west-central Argentina, where the beginning of a Paleozoic connection with the Pacific apparently existed, there occurs a well-known calcareous facies.

Cambrian faunas of the Cordilleran belt are said to show affinities particularly with the Pacific North American province, but, rather early in the Ordovician, faunas appear which indicate affinities with Atlantic-European waters. Possibly, connections existed from the north through the Caribbean, from the east across a developing Amazon geosyncline, and across the middle of the continent through Brazil where lower Paleozoic sediments of still insufficiently defined age occur.

In 1942 Middle Ordovician graptolite shales were identified in the center of a domal uplift in northeast Peru near the Brazilian frontier, further suggesting that the Amazon Paleozoic geosyncline may have developed this early in the Paleozoic era. Indeed, the 1938 geologic map of the Ministry of Agriculture of Brazil shows the oldest sediments of the Amazon trough as questionably late Cambrian, and they similarly map large areas of still insufficiently studied sediments extending across middle and eastern Brazil. Wherever early Paleozoic sediments are present in many parts of the world the Ordovician is commonly prominent. For this reason

and also from the fact that the Ordovician seas were more widespread than the Silurian or post-Caledonian seas in other parts of South America, it is felt that the Ordovician will be found represented in many of the occurrences of pre-Devonian age in Brazil.

Some of the older sediments of Brazil and Uruguay, occasionally mapped as early Paleozoic, may be late pre-Cambrian. However, it is the writer's opinion that, in the absence of recognizable fossils, geologists in general are apt erroneously to ascribe too great an age to sediments that show a high degree of metamorphism. This error has been made in South America with respect to highly metamorphosed sediments, even as young as the Cretaceous, where they occur in a belt that once was highly mobile.

No paleontologic evidence of Paleozoic deposits has yet been found in the Patagonian Andes or at any other place in South America south of 38° S. Lat. In the South Orkneys, about 700 miles southeast of Cape Horn, however, middle Ordovician species of arthropods and of graptolites are reported from sediments that have been altered to slates.

SILURIAN

Principally the lower and the very latest Silurian is found in South America. The early Silurian is present in the deeper parts of the Cordilleran seaway, particularly in Peru and Bolivia, as a continuation of the Ordovician graptolite-bearing sediments. It also occurs in the lower Amazon trough where it had possible connections westward, as shown, with the seas of the Cordilleran belt.

Some have considered the extensive Bambuhy and older series of east-central Brazil Silurian in age, based on a very meager and insufficiently studied fauna. The writer feels certain, on the basis of paleogeographic, stratigraphic, lithologic, and structural considerations, that these series are pre-Devonian. They may very well be Lower Silurian or Ordovician in age, or both. The paucity of fossils may be in part due to a semi-flysch character of much of the sediments, which were probably largely derived from the eastern mobile borderland and hinterland belt.

As in North America, the Silurian of South America may have its best or widest development in the eastern part of the continent. Sediments possibly Silurian in age occur in Matto Grosso and westward. There are indications of a possible connection between the Amazon and Cordilleran troughs across the Beni area of northern Bolivia. The extension of the Silurian seaway shown on Plate 3 across southern Brazil and Uruguay is very questionable.

The sea appears to have withdrawn extensively or completely from the present area of South America during much of the Silurian, probably in response to the Caledonian (Taconic) movements that so widely affected the earth. In latest Silurian time a readvance of the sea occurred which continued through the Lower Devonian. Sediments of this sea are present in the Cordilleran trough of Peru, Bolivia, and Argentina and in the trough then developing across middle Argentina. They probably are represented in the eastward transgressive advance of the Bolivian sea across Paraguay toward the Parana basin of south Brazil and north Uruguay.

There are insufficiently confirmed indications that Silurian sediments are present

in the Cordilleran belt of Colombia in the same trough belt occupied by the Cambro-Ordovician.

DEVONIAN

The sea advance which began in latest Silurian time spread eastward through the Chaco and Parana basin areas and along the middle Argentine seaway and remained throughout the lower Devonian. In the Cordilleran trough area of Bolivia and south Peru thousands of meters of flysch-type sediments accumulated. These were derived from lands newly raised by the Caledonian orogenies. In Bolivia and Peru sedimentation extended into the Middle Devonian. As a result of the Caledonian deformation in central Argentina the Cordilleran Devonian sea did not extend as far southward as did that of the Ordovician. In Brazil the Devonian consists of a prominent basal sand, overlain by shales which become somewhat more sandy at the top. Devonian sediments of South America are largely clastics—shales and sands. The Lower Devonian sea spread also through the Amazon trough, and far toward the south it covered the Falkland Islands.

In addition to its occurrence in the Central Cordilleran area, Middle Devonian is also present in the Amazon trough; and only Middle Devonian has so far been recognized in the Colombia-Venezuela trough, where, however, the occurrences are fairly widely distributed. Middle Devonian has not been recognized south of 20° S. Lat., unless a sandy facies which conformably overlies the lower Devonian shales in the Bolivian pre-Cordillera is of that age. Very recently field studies in the Maranhao basin, shown on the Devonian (Pl. 4) and on the Upper Carboniferous-Permian (Pl. 5), maps as extending southward from the area of the mouth of the Amazon, revealed the presence of a Devonian marine fauna; hence, a Devonian embayment apparently extended into this area.

Lower Devonian faunas of all basins south of the Amazon basin have a characteristic, related austral or southern aspect. The Amazon basin Lower Devonian sediments contain a similar fauna, with an admixture of northern forms. The Middle Devonian of Colombia, of the Amazon basin, and of Bolivia, while varying in ecologic conditions, all contain a related and essentially northern fauna, though in Bolivia there are thought to be present certain descendants of southern Lower Devonian types.

Upper Devonian time apparently found the seas withdrawn everywhere, though limited deposits of that age may yet be found in the areas of Middle or earlier Devonian sediments, especially in the troughs of greatest subsidence.

MISSISSIPPIAN

After the withdrawal of the Devonian seas from the area of the present continent, South America remained above sea level throughout the Mississippian period. Recently well-developed Mississippian marine sediments have been identified in San Juan and Mendoza in the embayment that extends eastward into west-central Argentina. This was a more or less continuous embayment. *Pentremites* and other Mississippian marine fossils have been reported in north-central Colombia.

In the Cordilleran belt of Peru and Bolivia, sediments are present which are thought to be Mississippian in age. These appear to be largely continental in facies, but it appears not improbable that marine representatives will be found in the deepest parts of the belt of sedimentary troughs. An occurrence of questionable Lower Carboniferous sandstone has been reported near Monte Alegre in the Amazon trough.

UPPER CARBONIFEROUS-PERMIAN

Middle Pennsylvanian marine sediments and certain other marine and continental beds, of less well-defined age, are known in the Cordilleran geosyncline of Peru, Bolivia, and northernmost Argentina. However, the first widespread advance following the retreat of the Devonian seas was of late Pennsylvanian-early Permian, or approximately Wolfcamp age. Sediments of this age were commonly loosely referred to as "Upper Carboniferous". They form one of the most widespread overlaps of the continent and cover approximately the same area as did the Devonian sediments. In contrast with the Devonian, however, continuously marine sediments were deposited only in the deeper western parts of the Cordilleran troughs and in the Amazon geosyncline (Pl. 5). Over the eastward extension of the Peru-Bolivia embayment, across the Chaco and Parana basin areas, the sediments have partly a continental-sea to brackish-water aspect, with only temporary intercalations of a true marine character. Southward, in middle Argentina, the formations are of an even more continental character, and the only marine sediments appear in the Cordilleran area of west-central Argentina and middle Chile.

The Cordilleran trough marine facies of Peru and northwest Bolivia consists largely of shales and sands and *Fusulina*-bearing limestones. Southward and eastward the limestones rapidly disappear, and the amount of sand and silt increases. In Argentina and southern Bolivia, and eastward through the Parana basin, glacial sediments appear at certain intervals in these beds. These locally faceted and striated but more commonly partly rounded constituents, as well as the accompanying finer clastics, were derived from neighboring highlands of eastern Brazil and Uruguay and from Argentina on the south, where glaciers developed in the so-called Gondwana ice age. In the marginal areas of Brazil and Uruguay and in the southern areas in Argentina (Pl. 5) these sediments are largely terrestrial or fresh-water in origin. They contain the characteristic *Gangamopteris* or Gondwana flora of the southern hemisphere, and associated coal beds. In the deeper parts of the basins in southern Brazil, Uruguay, Paraguay, southern Bolivia, and northern Argentina the clastics were carried by streams and sometimes directly by glaciers or icebergs into waters that were in large part marine, and they contain a marine fauna.

The Amazon basin sediments, which make up a large part of the section in that basin, are of a similar, late Carboniferous to early Permian age, but the faunas are said to show a much closer affinity to those of North America, though still containing some of the forms of the Cordilleran trough. In northwest Peru and southern Ecuador occur marine shales and other sediments of this age in good development. Northward, in Colombia and western Venezuela, marine late Carboniferous-early Permian is locally very well developed. Continental beds also occur which contain

the remains of a land flora. Far toward the south, Carboniferous continental glacial deposits overlap the Devonian in the Falkland Islands.

A controversy has long raged over the age of the Gondwana glacial deposits of South America. Some have preferred to place them in the late Carboniferous, others in the mid-Permian. In Bolivia and Argentina and in Paraguay, Uruguay, and Brazil there is a later series of Permian beds which may be mid-Permian or approximately Leonard in age, which is also the age given for some post-Wolfcamp Permian marine beds locally present in Peru and in Colombia. These later sediments of Brazil and other southern areas were deposited in an interior sea of similar outline to that of the earliest Permian, but they are predominantly of fresh-water character. In many places over the areas these deposits rest disconformably on the older Gondwana sediments without noticeable difference of dip. In Brazil and adjoining areas a widespread zone of pyrobituminous shales, generally known as the Iraty shales, occurs in these deposits. In numerous outcrops in Argentina and southernmost Bolivia well-faceted and striated clastics of a distinctly glacial origin occur near the middle of this upper series and prove the existence of a second period of glaciation in those areas.

TRIASSIC

By the close of the Paleozoic the seas had completely withdrawn from the area of the continent and do not appear again until Upper Triassic (Keuper) time (Carnian and Norian stages). Some plant-and coal-bearing deposits in Peru have been considered mid-Triassic. In South America then, as in North America and many other parts of the world, the most widespread deposition occurred in the Upper Triassic (Pl. 6).

Marine Upper Triassic of the Carnian and Norian stages occurs in limited development in southern Ecuador, Peru, and Bolivia. No Triassic marine deposition is known in South America below these stages. The most characteristic marine Triassic formation is a limestone which is locally bituminous and commonly dolomitic and cherty, with silicified fossils and nodules. Eastward and southward (and to a much greater extent than in the late Carboniferous—early Permian) the Upper Triassic sediments become continental.

Marine intercalations of thin limestones, together with marls, silts, and shales, occur in the upper Passa Dois of the Parana basin of Brazil and Uruguay. There has been much controversy over the age of the Passa Dois. It is a perfectly conformable sequence. Yet, while the lower part has always been recognized as Permian some of the marine intercalations above were quite definitely considered to be Upper Triassic on the basis of the contained faunas. A recent restudy of these faunas in Brazil has resulted in the conclusion that they are Permian and not Upper Triassic.

Definitely established Upper Triassic sediments disconformably overlie the zone of marine intercalations. These consist of silts and sands, and the Triassic sequence closed with a widespread heavy-bedded sand deposition. Extensive basic flows are intercalated in the upper part of, and follow, this prominent sandstone. The Triassic of Brazil contains a flora and a reptilian fauna which indicate its Upper Triassic age.

In central and western Argentina Triassic continental sands and other clastics disconformably overlie and, in some areas, overlap beyond the Permian deposits,

These continental clastics grade westward into marine Upper Triassic sediments of the Chilean trough. As shown by the maps, this trough was now becoming more prominent, and it continued so through the Jurassic and much of the Cretaceous. The Triassic fauna of South America appears to be mostly of a Pacific character and is related to the western Trias of North America.

No marine Triassic is known north of southern Ecuador. However, northward, in Colombia and western Venezuela, certain red and varicolored clastics, commonly referred to as the Giron series, probably are in part of Upper Triassic age. Characteristically, these sediments contain volcanic lavas and tuffs, as do so many of the late Triassic rocks of South America and many of the western-most deposits of North America.

In British Guiana, southern Venezuela, and adjoining parts of Brazil occur the prominent Roraima sandstone mesas with associated basic lavas. These sandstones are similar to the widespread late Triassic sandstones of central and southern Brazil; the associated trap flows in the various areas are mineralogically similar. The Roraima sandstones, as well as certain similar mesa-forming sandstones on the west in Colombia, may accordingly be of Upper Triassic age, though they may be somewhat younger.

The volume of the basic, but ordinarily olivine-free, trap flows centering in south Brazil is probably the largest recorded on present lands in the earth's history. The main part of these flows spread over a maximum width of nearly 1000 kilometers and a length of fully 2000 kilometers. They cover much of southern Brazil, eastern and southern Paraguay, northern Uruguay, and northeastern Argentina with thicknesses ranging from 100 to well over 1000 meters. The flows are similar in age and mineralogic type to the Palisade flows of the Hudson River and certain other Triassic basalts of the western hemisphere.

In west-central and southern Argentina and adjacent Chile occur other widespread, less basic Triassic extrusives. These include porphyritic rocks, so-called keratophyres, melaphyres, and their equivalent tuffs. Not all of these are Triassic in age for this type of intrusive and extrusive activity continues in the Jurassic and even somewhat later along the Andean mobile belt.

The marine and fresh waters withdrew at the end of the Noric. Continental deposits in north Mendoza and adjacent areas of West-Central Argentina, long considered to be Rhaetic in age, are now thought to be eastward equivalents of the Upper Triassic marine sediments that lie in the deeper basin on the west. The same may be true of most of Triassic continental deposits that occur widely in Argentina south of 27° S. Lat.

LOWER AND MIDDLE JURASSIC

In South America as in North America, and indeed in other parts of the world, the close of the Paleozoic and the opening of the Mesozoic brought a withdrawal of the extensive marine waters, together with an increase in continental deposition. At the same time there was initiated a new pattern of geosynclinal development which we see in the gradual change in the paleogeography toward the Jurassic and later periods.

By Lower Jurassic (Lias) time the new Chilean geocyncline, which was developing in the Triassic or even earlier, attained prominence. It extended for a distance of 30° of latitude, or from about 15° to 45° S. Lat. The geosyncline was much wider than that shown on Plate 7 which reflects the effect of the considerable post-depositional folding of the Andes. It is not certain that the Chilean geosyncline connected with that shown on the north in Peru. However, faunal data indicate a connection during the Lias and perhaps other stages.

Deposition was not continuous in the Chilean and Peruvian geosynclines during the Jurassic. Lias shales and limestones covered most of the areas outlined. There was some withdrawal of the seas in the Upper Lias, particularly in Peru. Marine Lias is known at El Banco in Colombia. This sea probably extended in along the main western trough of the embayment. The continental Giron beds in Colombia and equivalent beds in Venezuela, already referred to in connection with the Triassic, are thought to also include sediments of Jurassic age.

The sea readvanced in the Bajocian age of the lower Middle Jurassic (Dogger) over most of the Lias areas of Peru and Chile and appears to have overlapped beyond the Lias in northern Chile and southern Peru. The seas then retreated so that the upper Dogger, Bathonian stage, of the Middle Jurassic is completely lacking, at least as a marine facies.

A readvance in the Callovian are spread Callovian stage limestones and shales over all of the northern and much of the middle and south-central parts of the Chilean geosyncline. Callovian sediments are not definitely recognized in northern Peru. If they were deposited there, as seems quite possible, they may have been largely eroded during the diastrophisms that followed.

The moderate orogenic movements which caused the several marine recessions from late Triassic time onward were followed at the close of Callovian time in the Upper Jurassic by more severe orogenic movements. These led first to a closing off of extensive areas of the sea and the deposition of much anhydrite and/or salt and associated sediments in both the Chilean and Peruvian basins during the Oxfordian age. The extravasation of much volcanic material on the western side of the Chilean trough may have been partly responsible for the isolation of that basin. It is of interest that salt and other precipitates of approximately Oxfordian age occur in Colombia, the Isthmus of Tehuantepec, the Gulf Coast of North America, the Mississippi Valley, Chile, Argentina, Peru, and other parts of the world.

Corallian and Kimmeridgian stage sediments appear to be largely or completely absent in the geosynclines, though representatives of these stages may later be found. The most severe Jurassic orogenic movements occurred in late Jurassic, possibly Kimmeridgian time. This corresponds roughly with the so-called Nevadan revolution of North America. Various low arches, principally along the eastern Cordillera of Peru, developed at this time.

As in western North America, the close of the Jurassic in the Portlandian or Tithonian age witnessed an extensive readvance of the seas and a deposition that continued on through the early Cretaceous. The paleogeography of the Tithonian is shown along with that of the Neocomian on Plate 8.

TITHONIAN-NEOCOMIAN

The transgression which began in the Tithonian or closing stage of the Jurassic continued into the early Cretaceous. The paleogeography of the Tithonian and that of the early Cretaceous (Neocomian) are essentially similar. Except for certain limited deposition breaks in Peru and possibly other places, they may be treated as a unit. This unit has its approximate counterpart in the Pacific belt of North America, in Mexico, in the subsurface of the lower Mississippi Valley, in the Wealden of England, France, and Spain, and in other regions.

In the Chilean trough, Tithonian brown and black shales and limestones are followed conformably by Neocomian shales, limestones, and sandstones. Most of this sequence is marine. During the period the trough rapidly extended southward from northern Patagonia and probably northward through Tierra del Fuego, permitting ingress of southern faunas and mixture with the Indo-Pacific faunas that prevailed at this period along the west coast of the Americas. Paleozoic and early Mesozoic marine sediments have not been definitely recognized in southern Patagonia or on Tierra del Fuego. Just as they do in the north Venezuelan Andes, the Cretaceous formations appear to transgress directly upon the crystalline basement, though local occurrences of older sediments may one day be identified in the south Patagonian Andean belt.

In Peru marine sediments of the period are well developed on the coastal belt in the region of Lima. Here the Valanginian and Hauterivian stages of the Neocomian are particularly well represented. Eastward, toward the late Jurassic arch or arches, which, as already pointed out, developed along the belt of the present eastern Cordilleras, there is a change to a mixed marine and continental facies bearing some coals. In northern Peru, still little-known coals of this age occur, which may rank among the most important in volume and quality in South America. The earlier Tithonian, largely marine facies, is best represented in the northern and northwestern part of the geosyncline, while it is mainly the Neocomian that extends into the upper part of the embayment south of 9° S. Lat. East of the Eastern Cordilleran arch the Tithonian also thins out southward, and the Neocomian appears to consist largely of continental red or varicolored clastics, including much cross-bedded, possibly in part windblown, sandstones.

The late Jurassic-Neocomian sea of Colombia also spread eastward from the Pacific and connected across northern Venezuela and Trindad. From Trinidad to Peru the faunas of the seaways appear to have their main affiliation or connection with the Tethys faunas of Europe. While on regional and paleontological grounds it appears that the Cretaceous seaways extended through northern Colombia, there is on the basis of present information some question whether the area covered by the seas across north Colombia was as extensive as is shown on the Cretaceous maps (Pls. 9–11).

In the newly developing Bahia embayment of the east coast of Brazil continental or brackish, possibly estuarine sediments of apparent pre-Albian age are included on the Neocomian paleogeographic map, though they may be Aptian in age.

APTIAN-ALBIAN-LOWER CENOMANIAN

The paleogeography of the continent in Aptian-Albian-Lower Cenomanian time, which is approximately equivalent to the Comanchean of the Texas Gulf coast is shown on Plate 9. At the southern end of the continent, the seas had largely withdrawn south of 47° S. Lat., which area from this time onward became a prominent center of subsidence and deposition. Northward in this embayment, and in the Neuquen-Mendoza area farther northward, marine deposition gave way to a more continental facies in this period.

In the Peruvian embayment the Pacific seas spread inland and southward in the Barremian, Aptian, Albian, and Lower Cenomanian, depositing a marine shale, limestone, and sand facies. The Cenomanian, though spreading widely southward in Peru and Bolivia, is not generally of great thickness and is absent in many places, probably as a result of erosion during the mid-Cretaceous withdrawal of the sea, and subsequently. The base of this transgressive series is a prominent beach or near-shore type of sandstone, which appears to transgress time as the sea advanced, somewhat as does the Nubian sand facies of similar age in the eastern Mediterranean, or the basal Comanchean sands of the United States.

In the Colombia-Venezuelan seaway, a similar marine transgression and deposition mark the stages of this period. In the Bahia embayment, marine sedimentation appears for the first time in the Albian. This heralds the beginning of a taphrogenic breakdown of eastern lands, permitting the sea to reach the present coastal area of the continent for the first time since the mid-Paleozoic seaways crossed the present coast line.

LATE CENOMANIAN-TURONIAN-LOWER SENONIAN

Plate 10 pictures the paleogeography of the Upper Cretaceous from the late Cenomanian and Turonian through the Lower Senonian. The sediments of this period are the approximate equivalent of the Gulf series in the southern United States and of the Benton-Niobrara-Pierre of the Rocky Mountain front.

In the southern or Patagonian embayment there was marine deposition south of about 47° S. Lat., north of which there was gradation toward, and interfingering of marine facies with, a brackish and continental facies. The topmost sediments of the series in the continental facies areas contain the bones of dinosaurs, as did the late Cretaceous swamps of Coahuila and Chihuahua, Mexico, and of Texas and Rocky Mountain basins.

In the Peruvian embayment the sea withdrew during the Cenomanian. Much of the Cenomanian and some of the Turonian appears to be missing over wide areas of the basin. In the northern part of the geosynclines, in north Peru and Ecuador, the presence of Turonian marine sediments attests the reinvasion of the sea. The sea advanced rapidly through the Upper Turonian and Lower Senonian, spreading very widely in these stages when the bulk of the Upper Cretaceous sequence of marine shales, sandstones, and limestones was deposited.

In the Colombia-Venezuelan seaway there was the same mid-Cretaceous retreat and readvance of the sea. The Upper Cretaceous transgression, as in Peru, spread

more widely over the foreland than did any of the previous seas in this region. The backlands were beginning to rise, pushing the principal geosyncline forward. Embayments in the Bahia and Rio Grande do Norte coastal areas of Brazil also received marine deposits during this period.

As mentioned previously, higher land prevailed in the east, and lower lands in the west during most of Paleozoic and Mesozoic history. In Upper Cretaceous time this situation began to reverse itself as the first incipient Andean uplift movements, forerunners of greater movements in the Tertiary, started to change the continental surface to a more level position.

In addition to a much wider overlap of the forelands by the seas, there developed, as a result of the levelling process, extensive interior fresh-water lakes, in which clastic sediments and some locally occurring calcareous beds, were deposited. These Upper Cretaceous fresh-water deposits include the Cayua and Bauru facies which are spread widely over central Brazil. In Patagonia, also, the levelling process is reflected in the far eastward spread of the semicontinental deposits, which carry the dinosaur remains in their highest beds. Similar dinosaur-bearing beds occur in southwest Uruguay and adjacent Entre Ríos.

LATE SENONIAN-PALEOCENE

Plate 11 shows the paleogeography of South America during the period of the late Senonian through the Danian-Paleocene. At the close of the lower Senonian there was a rather general sea retreat in most areas. In places, such as close to the axes of deformation along mobile belts, the deformation was severe; but over wide areas the unconformity is not so noticeable as that of the main Laramide deformation immediately following the Paleocene.

In the Magallanes area of southern Argentina and Chile marine clastic deposition continued during much of the period. Farther northward in Patagonia, in the Comodora Rivadavia or San Jorge embayment and in the long northwest-trending Rio Negro embayment, marine, brackish, and continental beds of late Senonian-to-Paleocene age disconformably overlap Lower Senonian in embayments from the Atlantic. In addition to the disconformity at the base, at least one other occurs within the series itself in these embayments.

Under the city of Buenos Aires basement rocks have been found at about 300 meters depth. Between it and the Sierra Tandil about 250 kilometers to the south lies the axis of a Miocene embayment. Beneath this we have suggested the possibility of existence of a late Cretaceous embayment.

Farther north on the Atlantic coast, marine deposition occurred in the Bahia and Rio Grande do Norte embayments and in a very narrow belt along other parts of the coast.

In the Peruvian embayment the sea withdrew at the end of the prominent Senonian deposition. In the succeeding basin, which was somewhat narrower because of the now considerably emerged Andean belt on the southwest and emergence of the foreland to the east, there was deposited a series of reddish to gray sediments of largely brackish to continental facies but embracing certain marine intercalations. The sediments vary in facies and thickness along the trough of the embayment.

From the limited fauna and from stratigraphic considerations, these sediments appear to range from late Senonian to earliest Tertiary or Paleocene.

The remnants of a trough within the Andean belt of Peru contain thick continental beds (such as the Rimac series) which have been considered late Cretaceous in age but which are more likely wholly or largely Tertiary.

Along the Pacific coast of Peru and Ecuador occur latest Cretaceous-Paleocene sediments of entirely marine facies. South of Valparaiso on the western coast of Chile there is a narrow coastal overlap of marine sediments reported to be late Senonian in age.

In the Colombia-Venezuela geosynclinal belt the late Cretaceous-early Tertiary time interval varies laterally in the extent to which it is represented by sediments. In places beds as young as middle to upper Eocene or younger rest on strata as old as Lower Senonian or older. In other, deeper basin areas this interval is partly to largely filled with corresponding shales and sands bearing late Cretaceous to Paleocene marine faunas. An overlap of this period occurs along the western part of the north Panama coast.

Throughout the western hemisphere, and indeed in most parts of the world where Paleocene sediments occur, these sediments in their facies and general affiliations appear more akin to the Cretaceous than to the Tertiary proper, whose first sediments commonly follow in middle Eocene time, or even later.

EOCENE

While early orogenic movements initiating the uplift of the Andean belt occurred within the Cretaceous, the first major Andean movement of the Tertiary period followed the Danian-Paleocene stage and had its climax in the early Eocene. This corresponds to the main so-called Laramide movement in the North American part of the Cordillera and to diastrophisms at the same time in other parts of the world.

Except in the deeper basin parts, lower Eocene sediments are not prominently developed in most areas. The sea advanced again following the first Andean movement and, though interrupted by relatively less important disturbances and deposition hiatuses, the middle and upper Eocene witnessed the widest advances of the sea and received the bulk of the sediments of the Eocene epoch within the present limits of the continent (Pl. 12).

In the southern Patagonian or Magallanes embayment the Eocene appears to be represented by a clastic, largely marine facies. In the Comodora Rivadavia or San Jorge embayment a continental facies bearing an Eocene land fauna is represented. Sediments of the same age are reported in the Rio Negro embayment, and, though unconfirmed, they may also be present in the Buenos Aires embayment. Eocene sediments have been reported from the largely continental facies of the Tertiary in the Bahia embayment and along the coast line of Alagoas and Sergipe on the north.

Eocene sediments occur in a thick clastic marine sequence in the coastal embayments of northwest Peru and in southwestern and western Ecuador. A number of disconformable hiatuses are present in these largely middle and upper Eocene deposits. While Eocene sediments have not been definitely identified east of the Andes it seems likely that they may occur there in a brackish to continental facies which had westward connections with the coastal areas.

Eocene, mainly middle and upper, is well represented by a thick series of marine to semimarine clastic sediments through the basins of northern Venezuela and Colombia, with southward embayments of a less marine character. Sediments of similar age occur in Panama.

OLIGOCENE-EARLY MIOCENE

The second main Andean movement had its climax in early Oligocene time. This disturbance was commonly marked by a withdrawal of the sea starting in late Eocene or early Oligocene and, in many places in northwestern South America, by moderate to severe deformation followed by an overlap of middle to upper Oligocene.

A well-defined marine transgression of middle-to-late Oligocene time occurred in the Patagonian embayments. Transgression began somewhat earlier toward the south, and sedimentation reached somewhat greater thicknesses successively from north to south in the several embayments shown on Plate 13. There has been some difference of opinion among paleontologists concerning the position of the boundary between the Oligocene and the Miocene in many parts of the world. In general, South American Oligocene marine sedimentation continued into or through the lower Miocene, though there is some marginal or headward and also upward gradation into brackish and continental deposits.

Little is known of the extent to which transgression and deposition of the upper Oligocene-lower Miocene period occurred in the Buenos Aires or La Plata embayment. There are indications that the maximum transgression in this embayment was somewhat later in the Miocene. (See Plate 14.) Likewise, in the Bahia embayment the age of the largely nonmarine Tertiary sediments is still uncertain.

On the west coast of Chile sediments of this period appear to be represented in the small Arauco embayment. Marine overlaps of this period are well represented in the coastal embayments of western and northwestern Peru and Ecuador.

In Venezuela and Colombia a prominent Oligocene-lower Miocene sea transgressed from the northeast and north more or less widely across Eocene and older rocks. East of the Andes this transgression extended as a semimarine to brackish and continental facies into Ecuador and Peru, though the existence of archipelagic conditions at the time along the Andean belt would have permitted connections with the Pacific. Eastward, along the middle and lower Amazon trough, all the Tertiary deposition appears to be continental in character.[1]

MIDDLE MIOCENE

The transgression of seas which followed the second major Tertiary orogenic-epeirogenic movement of early Oligocene age and which spread through the upper Oligocene and early Miocene continued, with minor interruptions marked by lesser hiatuses, through the middle Miocene. Clastic deposition, derived mainly from the rising Andean belt, was widespread. Sedimentation was so relatively rapid in the middle Miocene basins and embayments that there developed a general retreat

[1] Little is known concerning the exact age of the continental sediments along the Amazon Basin. Additional research since the writing of this paper indicates that the greater part of the Tertiary deposits along the Middle Amazon are of Pliocene rather than Miocene age.

of marine and brackish conditions from the positions attained by the sea advances during the Oligocene and early Miocene.

The relative extent of this largely continental deposition and the changing conditions may be visualized by comparing the middle Miocene map (Pl. 14) with that for the upper Oligocene-early Miocene (Pl. 13). Some of the interior continental deposits shown on the middle Miocene map may be in part equivalent in age to earlier Miocene.

The extent of the La Plata marine embayment northward and northwestward is as yet incompletely determined. In the Oran basin of Jujuy and central Salta in northern Argentina the local very high salinity of formation waters indicates a temporary isolation of this area.

Continental deposition continued throughout the pre-Andean and Amazon troughs, while, in the embayments of the Pacific coast, conditions remained prevailingly marine. With the increasing rates of deposition there was also in Venezuela and Colombia a rather general recession of marine facies toward the deeper outer areas of the embayments.[2]

UPPER MIOCENE

The increased rate of clastic deposition in the middle Miocene brought about a filling of the basins preliminary to the third major Andean orogenic and epeirogenic uplift which had its climax in the late Miocene. The upper Miocene map (Pl. 15) shows the approximate conditions of upper Miocene time immediately preceding this main movement, which in general corresponds with the so-called Attic diastrophism of Europe.

PLIOCENE

Marine deposition of Pliocene time is rather well developed in many basins of Europe and the Mediterranean regions and in other areas of the eastern hemisphere, as well as in the basins along the western coast of North America. In South America, Pliocene marine deposition is restricted to the outer parts of certain embayments, though continental deposition continued in the old geosynclines of the interior throughout Pliocene and much of Pleistocene time (Pl. 16). The largely continental sedimentation was brought to a close in all except limited localities by the fourth major Andean orogenic and epeirogenic diastrophism which had its climax in early Pleistocene time when the seas withdrew outside the present continental shelves along most of the coast lines.

A well-defined Pliocene marine embayment was present in southern Patagonia, and limited marine deposition of this period occurred in the La Plata embayment. On the northern and western coasts of the continent marine deposition was of very limited extent during the Pliocene.

[2] The two very small patches of continental deposits appearing on the Middle Miocene map (Pl. 14) near the Brazil coast and immediately west of the 45th meridian were placed on this map through oversight. They should be on the Pliocene map (Pl. 16). They represent the partially downfaulted Taubuté and Tremenbé lake basins, whose deposits appear to be largely Pliocene, based mainly on their contained fish remains.

Glaciers developed in Pleistocene time in the southern section of the Cordilleras, and the effects of this period of glaciation are general over the southern half of Patagonia.

Beginning in the Mesozoic and continuing throughout the Tertiary, but most particularly in late Tertiary and Quaternary time, there is much evidence of taphrogenic breakdown and marked subsidence of the Pacific and Atlantic border belts, as well as in the Caribbean-Gulf of Mexico areas. Along the whole length of the Andes and in the Mexican, Central American, and Antillean regions, as well as in western North America, considerable volcanic activity and extravasation of lavas accompanied the mountain uplift and the down-faulting and subsidence of border areas beneath the seas.

SELECTED BIBLIOGRAPHY

Aguerrevere, S. E., and Zuloaga, G. (1937) *Geological notes on the central part of the Cordillera de la Costa, Venezuela*, 2d Venezuelan Geol. Cong., Bol. Geol. Min., p. 3–22.

———*et al.* (1939) *Exploración de la Gran Sabana, Venezuela*, Min. Fom. 3, vol. 19, p. 501–729.

Aid, Kenneth, and Bauernschmidt, A. J., Jr. (1928) *Geology of southwestern Mendoza Province, Argentina*, Am. Assoc. Petrol. Geol., Bull., vol. 12, p. 693–714.

Ameghino, C. (1890) *Exploraciones geológicas en la Patagonia*, Inst. Geol. Argentina, Bol. 11.

Ameghino, F. (1906) *Les formations sédimentoires du Crétacé supérieur et du Tertiare de Patagonie*, An. Museo Nacion., vol. 8, Buenos Aires.

Anderson, F. M. (1928) *Notes on Lower Tertiary deposits of Colombia and their molluscan and foraminiferal fauna*, Calif. Acad. Sci., Pr., 4th ser., vol. 17, no. 1.

———(1929) *Marine Miocene and related deposits of north Colombia*, Calif. Acad. Sci., Pr., 4th ser., vol. 18, p. 73–213.

Anderson, J. L. (1945) *Petroleum geology of Colombia, South America*, Am. Assoc. Petrol. Geol., Bull., vol. 29, p. 1065.

Andersson, J. G. (1907) *Contributions to the geology of the Falkland Islands*, Wiss. Ergebn. d. Schwed. Sudpol—Exped. 1901–1903, Stockholm.

Attwood, G. (1879) *A contribution to South American geology*, Geol. Soc. London, Quart. Jour., vol. 35.

Aubert de la Rue, E. (1933) *Contribution à l'étude géologique de la Cordillere occidentale des andes de Colombia*, Acad. Sci. Paris, C. R., t. 197, no. 18, p. 991–992.

Baker, C. L. (1923) *The lava field of the Parana Basin*, Jour. Geol., vol. 31.

Barbosa, O. (1936) *Resumo da geologia do Estado de Minas Geraes (Résumé of the geology of the State of Minas Geraes, Brazil)*, Estado de Minas Geraes, Serviço Geol., Bol. 3, 1934. Geological map by D. Guimaraes and O. Barbosa (Abstract), Neues Jahrb., Ref. III, (5), p. 786.

Bauernschmidt, A. J., and Aid, K. (1928) *Geology of southwest Mendoza Province, Argentina*, Am. Assoc. Petrol. Geol., Bull., vol. 12, p. 693.

Beder, R. (1923) *Sobre un hallasgo de fosiles pérmicos en Villarrica*, Acad. Nac. Cienc., Bol. 27, Córdoba.

———and Windhausen, A. (1918) *Sobre la presencia del Devónico en la parte media de la república del Paraguay*, Acad. Nac. Cienc., Bol. 23, Córdoba.

Behrendsen, O. (1891–1892) *Zur Geologie des Ostabhanges der argentinischen Kordillere*, Zeit. Deutsch. Geol. Gesell., vols. 43, 44. (Abbreviated version in Actas Acad. Nac. Cienc. Cordoba, vol. 7, 1922.)

Berry, E. W. (1922a) *The Mesozoic flora of Peru*, Johns Hopkins Univ., Stud. Geol., vol. 4, t. 1–3, p. 45–70.

———(1922b) *Carboniferous plants from Peru*, Johns Hopkins Univ., Stud. Geol., vol. 4, t. 1–7, p. 10–42.

———(1922c) *Marine Upper Cretaceous and new Echinocorys from the Altiplanicie of Bolivia*, Jour. Geol., vol. 30, p. 227–231.

Berry, E. W. (1924) *Mesozoic plants from Patagonia*, Am. Jour. Sci., 5th ser., vol. 7, no. 42, p. 473.
———(1932) *Sketch of the geology of Bolivia*, Pan.-Am. Geol., vol. 57, May.
———(1941) *Mesozoic and Cenozoic plants of South America, and the Antilles*, 8th Am. Sci. Cong., Washington, 1941, Pr., vol. 4, p. 365–373.
———and Singewald, J. T., Jr. (1922) *The geology and paleontology of the Huancavelica Mercury district*, Johns Hopkins Univ., Stud. Geol., vol. 2, p. 1–100., 10 t.
———and Swartz, F. M. (1925) *Contributions to geology and paleontology of South America*, Johns Hopkins Univ., Stud. Geol., vol. 6.
Bodenbender, G. (1892) *Sobre el terreno Jurásico y Cretaceo en Los Andes, Argentina, entre el Rio Diamante y Rio Limay*, Acad. Nac. Cienc. Bol., vol. 13, Córdoba.
———(1896) *Sobre la edad de Algunas Formaciones Carboníferas de la República Argentina*, Rev. Mus. de La Plata, vol. 7, p. 129.
———(1897) *Davano y Gondwana en la República Argentina*, Acad. Nac. Cienc., Bol., vol. 15, Córdoba.
———(1902) *Contribución al conocimiento de la Precordillera de San Juan y Mendoza y de las Sierras centrales de la República Argentina*, Acad. Nac. Cienc., Bol., vol. 17, Córdoba.
———(1905) *La Sierra de Córdoba. Constitución geológica y productos minerales de applicación*, An. Minist. Agric., vol. 1, no. 2, Buenos Aires.
———(1911) *Constitución geológica de la Parte meridional de La Rioja y regiones limítrofes*, Acad. Nac. Cienc., Bol., vol. 19, Córdoba.
———(1916) *El Nevado de Famatina*, Acad. Nac. Cienc., Bol., vol. 21, Córdoba, p. 100–182.
———(1929) *Triásico y Terciario en la falda oriental de la Sierra de Córdoba*, Acad. Nac. Cienc., Bol., vol. 31, Cordoba.
Boehm, K. E. (1937) *Contribution to the knowledge of the Liassic stratigraphy in the south of Mendoza Province*, Inform. Petrol. (B.A.), Bol., vol. 14, no. 151, p. 21.
Bonarelli, G. (1921) *Tercera contribución al conocimiento geológico de las regiones petrolíferas subandinas del Norte (Prov. de Salta y Jujuy)*, An. Minist. Agric., Sec. Geol., vol. 15, no. 1, Buenos Aires.
———and Nagera, J. (1921) *Observaciones geológicas en las immediaciones del Lago San Martín*, Direc. Gen. Minas, Bol., vol. 27, Buenos Aires.
———and Pastore, F. (1918) *Bosquejo geológico de la Provincia de Tucumán*, Primera Reunión Nac. Argentina Cienc. Natur., Tucumán, 1916.—Buenos Aires, 1918–1919.
Bosworth, T. O. (1920) *Structure and stratigraphy of the Tertiary deposits in northwestern Peru*, Geol. Soc. London, Pr.
———(1922) *Geology of the Tertiary and Quaternary periods in the northwest part of Peru*, Macmillan, 434 pages.
———(1923) *Geology and paleontology of northwest Peru*, Macmillan and Sons, Ltd., London.
———and Craig, E. H. C. (1922) *Review of geology of the Tertiary and Quaternary periods in the northwest part of Peru*, I. P. T., vol. 8, p. 688.
Bowman, I. (1909) *Physiography of the central Andes*, Am. Jour. Sci., 4th ser., vol. 28, p. 197–217, 373–402, 28 figs.
———(1916) *The Andes of southern Peru. Geographical reconnaissance along the 73d meridian*, 336 pages, 203 figs., 7 maps, New York, Am. Geog. Soc.
Bracewell, S. (1938) *Geological reconnaissance survey of part of the Northwest district, British Guiana*, Geol. Survey Br. Guiana, Bull. 7, 37 pages.
———(1942) *Report on the area between Arakaka and Kokerit, Northwest District, British Guiana*, Geol. Survey Br. Guiana, Bull. 19, 32 pages.
Brackebusch, L. (1877) *Informe sobre un viaje geológico por las Sierras de Córdoba y San Luis, practicado en el año 1876*, Acad. Nac. Cienc., Bol., vol. 2, Córdoba.
———(1882) *Estudios sobre la formación petrolífera de Jujuy*, Acad. Nac. Cienc., Bol., vol. 5, Córdoba, p. 137–252.
Branner, J. C. (1889) *The Cretaceous and Tertiary geology of the Sergipe Alagoas basin of Brazil*, Am. Philos. Soc., Tr., n.s., vol. 16, p. 369–434.
———(1919) *Outlines of the geology of Brazil, to accompany the geologic map of Brazil*, Geol. Soc. Am., Bull., vol. 30, p. 189–338.

British Guiana Geological Survey (1934) *Reports, Georgetown, 1936*, 76 pages, geological maps.

Broggi, J. A. (1913) *La Silla de Payta y sus alrededores*, Bol. Minas 5.

———(1920) *Apuntes sobre la geología de Huánuco*, An. Cong. Nac. Ind. Minera., t. 7, p. 38–66, 2 tables.

———(1921) *Reconocimiento de la región costanera de los Departamentos de Tumbes y Piura*, Arch. Assoc. Per. Prog. Sci., t. 1.

Brüggen, H. (1910) *Die Fauna des Unteren Senons von Nord-Peru*, Beitr. Geol. Pal. Südamerika, 16, Neues Jahrb. Mineral, Geol., Paläont., Beilage Bd. 30, p. 717–788, 25–29, 17 figures.

Bruggen, J. (1913a) *Contribución a la geología del Valle del Huasco y del departamento de la Serena*, Soc. Nat. Minería, Santiago.

———(1913b) *Informe sobre las exploraciones geológicas de la región carbonífera del sur de Chile*, Soc. Nac. Minería, Santiago.

Buch, L. von (1850) *The Andes in Venezuela*, Zeit. Deutsch. Geol. Gesell., p. 339.

Burckhardt, C. (1900a) *Profils géologiques transversaux de la Cordillère Argentino-Chilienne*, An. Museo La Plata, Sec. Geol. Mineral., vol. 2.

———(1900b) *Coupe géologique de la Cordillère entre Las Lajas et Curacautín*, An. Museo La Plata, Sec. Geol. Mineral., vol. 3.

———(1903) *Beiträge zur Kenntnis des Jura und der Kreide der Kordillere*, Paleontogr., vol. 50.

Carlson, C. G. (1925) *Geological notes on a part of southern Trinidad, B. W. I.*, Econ. Geol., vol. 20, p. 153.

Caster, Kenneth E. (1941) *Paleozoic geography of South America with particular reference to the Devonian* (Abstract), Geol. Soc. Am., Bull., vol. 52, p. 1892.

Christ, P. (1927) *La coupe géologique le long du chemin de Mucuchachi à Sta. Barbara dans les Andes Vénézuliennes*, Eclog. Geol. helv., vol. 20, no. 3, p. 397–415.

Cizancourt, Henry de (1933) *Tectonic structure of northern Andes in Colombia and Venezuela*, Am. Assoc. Petrol. Geol., Bull., vol. 17, p. 211–228.

——— and Schneegans, D. (1936) *Geology of the petroliferous areas of South America and the islands of the Caribbean Archipelago*, An. Comb. Liq., vol. 11, p. 93.

Clarke, J. M. (1896) *As trilobitas do Grez de Ereré e Maecurú, Estado do Pará, Brazil*, Arch. Mus., Nac., vol. 9, Rio de Janeiro, p. 1–58 (Portuguese and English text).

——— (1899a) *A fauna siluriana superior do Rio Trombetas*, Arch. Mus. Nac., vol. 10, Rio de Janeiro, p. 1–48 (Portuguese and English text).

——— (1899b) *Molluscos devonianos do Estado do Para, Brazil*, Arch. Mus. Nac., vol. 10, Rio de Janeiro, p. 49–174 (Portuguese and English text).

——— (1913) *Fosseis Devonianos do Paraná*, Serv. Geol. Brasil, Mon. vol. 1, Rio de Janeiro (Portuguese and English text). 353 p.

——— (1920) *New Paleozoic crustaceans II: Crustacea of the Permian of Sao Paulo, Brazil*, N. Y. State Mus., Bull. 219, 220.

Coleman, A. P. (1926) *Ice ages, recent and ancient*, Macmillan Co., New York.

Cope, E. D. (1886) *A contribution to the vertebrate paleontology of Brazil*, Am. Philos. Soc., Pr., vol. 23.

Cossmann, M. (1925) *Descripcion des gastropodes mésozoiques de Nord-Ouest de l'Argentine*, Communic. Mus. Nac. Hist. Natural., Paleont. Invertebrados, no. 10, Buenos Aires.

Darrah, W. C. (1941) *Notas sobre la historia de la paleobotánica sud-americana*, Lilloa (Rev. Botanica), Tucuman, vol. 6, ent. 2, p. 213–239 (Spanish, English summary). Sketch map, 3 plates.

Darwin, Charles (1876) *Geological observations on South America*, 2d ed., London.

Derby, O. A. (1878) *Contribuição para o estudo da geologia do valle do rio S. Francisco*, Arch. Mus. Nac., 3, Rio de Janeiro, Brasil.

——— (1880) *A contribution to the geology of the lower Amazonas*, Am. Philos. Soc., Pr., vol. 8, p. 155–178.

——— (1894) *The Amazonian upper Carboniferous fauna*, Jour. Geol., vol. 2, p. 480–501.

——— (1906) *A serra do Espinaço, Brazil*, Jour. Geol., vol. 14, p. 374.

Dickey, P. A. (1941) *Pre-Cretaceous sediments in Cordillera Oriental of Colombia*, Am. Assoc. Petrol. Geol., Bull., vol. 25, p. 1789.

Dietrich, W. O. (1923) *The paleontology and stratigraphy of the Cretaceous and Tertiary of the Eastern Cordillera of Venezuela*, Zentralbl. Mineral., p. 181–187, Stuttgart, 1924.

——— (1935) *The stratigraphy of the Eastern Cordillera of Colombia*, E. Schweizerb. Verlagsbuchandlung, Stuttgart.

D'Orbigny, A. (1842–1846) *Voyage dans l'Amérique méridonale*, vol. 4, *Paléontologie*, p. 1–188, Edición española traducida y anotada por V. E. Marchant. La Paz 1907.

Douglas, J. A. (1914–1921) *Geological sections through the Andes of Perú and Bolivia; (Part I) From the coast of Arica in the north of Chile to La Paz and the Bolivian "Yungas,"* Geol. Soc. London, Quart. Jour., vol. 70, p. 1–53, t. 1–10 (1914); (*Part II*) *From the Port of Mollendo to the Inambari River*, Geol. Soc. London, Quart. Jour., vol. 76, p. 1–58, t. 1–6 (1920); (*Part III*) *From the Port of Callao to the River Perené*, Geol. Soc. London, Quart. Jour., vol. 77, p. 246–284, t. 15–20 (1921).

Douvillé, R. (1909) *Sur des Holcostephanidés et quelques autres fossiles rapportés du territoire du Neuquén par M. Recopé*, Soc. Géol. France, Bull., 4me. série, vol. 9.

Dreveruann, Fr. (1904) *The Lower Silurian in Venezuela*, Neues Jahrb. Mineral., Geol., Paläont., Jahrg.

Dunbar, Carl O., and Newell, N. D. (1946) *Marine early Permian of the central Andes and its fusuline faunas*, Am. Jour. Sci. vol. 244, p. 377–402, 457–491.

Du Toit, Alex. L. (1927) *A geological comparison of South America with South Africa* (*with paleontological contribution by F. R. Cowper Reed*), Carnegie Inst. Washington (Libr. L958).

Ells, R. W. (1911) *Trinidad and Barbados*, Min. Soc. Nova Scotia, vol. 16, p. 129.

Englemann, Rolf (1935) *Geology of Venezuelan Andes*, Am. Assoc. Petrol. Geol., Bull., vol. 19, p. 769–792.

Erichsen, Alberto I., and Löfgren, Axel (1940) *Geología de Goiaz a Cuiabá, Brazil*, Div. Geol. Min., Bol. 102, 38 pages, (English summary, p. 11–12).

Estorff, Fritz E. von (1946) *Tectonic framework of northwestern South America*, Am. Assoc. Petrol. Geol., Bull., vol. 30, p. 581.

Eugster, H. (1922) *The geology of eastern Colombia Cordillera*, Eclog. Geol. Helvetiae, vol. 17, no. 2.

Favre, F. (1908) *Die Ammoniten der unteren Kreide Patagoniens*, Neues, Jahrb. Mineral. Geol. Paläont., Beilage Bd. 25, Stuttgart.

Feruglio, E. (1927) *Apuntes sobre la constitución geológica de la región del Golfo de San Jorge*, An. Soc. Argentina, Estudios Geográficos Gaea, vol II, no. 2, Buenos Aires.

——— (1931) *Nuevas observaciones geológicas en la Patagonia Central*, Contrib. Prim. Reunion Nac. Geog., vol. 4, Buenos Aires.

——— (1933a) *Fossili liascici della valle del rio Genua* (*Patagonien*), R. Mus. Geol., Ann., vol. 9, Bologna.

——— (1933b) *La série mesozóica nelle Ande del Lago Argentino*, R. Mus. Geol., Ann., vol. 9, Bologna.

——— (1935) *Relaciones estratigráficas y faunísticas entre los estratos cretaceos y terciarios en la region del Lago Argentino y en la del Golfo de San Jorge* (*Patagonia*). Bol. Inform, Petrol., an. 12, no. 128, p. 69–93, Buenos Aires.

Forbes, D. (1861) *Report on the geology of South America, Part I, Bolivia and southern Perú*, Geol. Soc. London, Quart. Jour., vol. 17, p. 1–84.

Frenguelli, J. (1941) *El Terciario de las Regiones Australes de América Meridional*, 8th Am. Sci. Cong., Pr, vol. 4, p. 291–301.

Freyberg, B. von (1930) *Die Gondwana Schichten in Minas Geraes* (*Brasilien*), Zentralbl. Mineral., Geol., Paläont.

Fritzsche, C. H. (1919) *Eine Fauna aus Schichten der Kreide-Tertiärgrenze in der argentinischen Cordillere des südlichen Mendoza*, Centralbl. Mineral., Geol., Paläont.

——— (1923) *Neue Kreidenfaunen aus Südamerika* (*Chile, Bolivia, Perú, Colombia*), Neues Jahrb. Mineral., Geol. Palaont., Beilage Bd. 50, p. 1–56, 313–334, t. 1–4. Stuttgart.

Garner, A. H. (1925) *Suggested nomenclature and correlation of geological formations in Venezuela*, Am. Inst. Min. Metall. Eng., T.P., vol. 71, p. 1358–1368.

Geinitz, H. B. (1925) *Über rhätische Pflanzen und Tierreste in den argentinischen Provinzen La Rioja, San Juan y Mendoza*, Beiträge zur Geologie und Paläontologie der Argentinischen Republik, vol. 2, Paläont. Teil. Cassel, 1876. (Versión castellana), Actas Acad., Nac. Cienc., Tomo 8, entr. 3 y 4 Córdoba.

Gerhardt, K. (1897) *Beitrag zur Kenntnis der Kreideformation in Venezuela und Peru. Beitrag zur Kenntnis der Kreideformation in Colombien*, Neues Jahrb. Mineral., Geol., Paläont., Beilage Bd. 11.

Gerth, H. (1913) *Stratigraphie und Bau der argentinishen Kordillere zwischen dem Rio Grande und Rio Diamante*, Zeitschr. Deutsch Geol. Gesell., Bd. 65, Monatsber 11, Berlin.

——— (1915) *Geologische und morphologische Beobachtungen in den Kordilleren Südperus*, Geol. Rundschau, vol. 6.

——— (1921) *Fauna und Gliederung des Neokoms in der argentinishen Kordillere*, Centralbl. Mineral., vol. 12.

——— (1925a) *Estratigrafía y distribución de los sedimentos mesozóicos en los Andes Argentinos*, Actas Acad., Nac. Cienc., Córdoba, vol. 9.

——— (1925b) *La Fauna neocomiana de la Cordillera Argentina*, Actas Acad., Nac. Cienc., Córdoba, vol. 9.

——— (1926) *Die Fauna des Neokom in der argentinischen Kordillere, Teil III*, Geol. Rundschau, Sonderband XVIIa (Steinmann-Festschrift).

——— (1928) *Neue Faunen der oberen Kreide mit Hippuriten aus Nordperu*, Leidsche geol. Mededel., vol. 2.

——— (1935) *The geology of South America*, Gebr. Borntraeger, Berlin.

——— (1938a) *Rasgos generales de la historia geológica de la cordillera sudamericana*, Bol. Geol. Mineral., Caracas, Venezuela, t. 2, no. 2, 3, 4, p. 1–10 (Discussion p. 237), English edition, p. 1–10.

——— (1938b) *Stratigraphische und faunistische Grundlagen zur geologischen Geschichte des südantlantischen Raumes*, Geol. Rundschau, Bd. 30, H. 1–2, p. 64–79, 2 figs. (sk. maps).

——— (1939) *Die Kordilleren von Südamerika: Regionale Geologie der Erde* (Andree, Brouwer, u. Bucher), Bd. 3, Abschnitt IVb, 63 pages, 12 figs.

——— (1940) *Die Fortsetzund der venezuelanischen Kordilleren in den Antillenbogen*, Geol. Rundschau, Bd. 31, H. 3–4, p. 206–207.

Gottsche, C. (1878) *Über jurassische Versteinerungen aus der argentinischen Kordillere*, in Stelzner, Beitr. Geol. Paläont. argent. Republik, Paläont., Suppl. 3, Lief. 2.

Grantham, D. R., and Noël Paton, R. F. (1938) *Report on the geology of the superficial and coastal deposits of British Guiana*, Geol. Survey Br. Guiana (Georgetown), Bull. 11, 122 pages.

Groeber, P. (1918) *Estratigrafía del Dogger en la República Argentina*, Direc. Gral. de Minas, Bol. 18 B, Buenos Aires.

——— (1921a) *Pérmico y Triásico en la costa de Chile*, Rev. Soc. Argentine, Cienc. Nat., Bol. 5, Buenos Aires.

——— (1921b) *Algunas observaciones referentes a la estratigrafía y tectónica del Jurásico al sud del Río Agrio cerca de Las Llajas (Terr. del Neuquén)*, Rev. Soc. Argentina, Cienc. Nat., Bol. 4 F, Buenos Aires.

——— (1924) *Descubrimiento del Triásico marino*, Communicaciones Museo Nac. Hist. Nat., Bol. 2, Buenos Aires.

——— (1925) *Bemerkungen zur stratigraphie des Lias von Piedra Pintada (Zaina-Yehua)*, Neues Jahrb. Mineral., Geol., Paläont., Beilage Bd. 52, Abt. B, Stuttgart.

——— (1929) *Lineas fundamentales de la geología del Neuquén, sud de Mendoza*, Direc. Gener. de Minas Pub., Bol. 58, Buenos Aires.

——— (1939) *Mapa geológico de Mendoza:* Physis (Soc. Argentina Cienc. Nat.), t.14 (No. 46), p. 171–220, 2 figs., colored geologic map, 1:2,000,000.

Grzybowski, J. (1899) *Tertiary deposits of northern Peru and their mollusk fauna*, Bol. Minas., ser. 3, tomo 8–9, p. 11, Lima, 1937. (Translation by G. Petersen of paper published in Neues Jahrb. Mineral. Geol. Paläont., Bd. 12, p. 610–664, t. 15–20.

Guimarães, D. (1931) *Contribuição a Geologia do Estado de Minas Geraes*, Serv. Geol. Brasil, Bol. 55, Rio de Janeiro.

——— and Barbosa, O. (1935) *Mappa Geológico do Estado de Minas Geraes, 1:1,000,000*, Minas Geraes, Serv. Geol., Bol. 3, 1934. Single sheet abstract, Mineral. Mag., 6 (4), p. 160–161.

Guppy, R. J. L. (1864) *On later Tertiary deposits at Matura on the east coast of Trinidad*, Sci. Assoc. Trinidad, Tr., p. 33, (Reprinted Geol. Mag., vol. 11, p. 256, Bull. Am. Paleont., vol. 8, no. 35, p. 13, 1921).

——— (1877) *On the physical geography and fossils of the older rocks of Trinidad*, Sci. Assoc. Trinidad, Pr., vol. 2. (Reprinted Bull. Am. Paleont., vol. 8, 1921).

Haas, M. W., and Hubman, R. G. (1937) *Notes on the stratigraphy of the Bolivar coastal fields, Maracaibo Basin, Venezuela*, Venezuelan Geol. Cong., Bol. Geol. Mineral., p. 123–164.

Hagerman, Tor H. (1933) *Informe preliminar sobre el levantamiento geológico del Departamento de Santa Barbara en la Provincia de Jujuy*, Bol. Inform. Petrol., Buenos Aires, Ann. 10, no. 107, p. 451–495, (map 1:250,000)

——— (1936a) *Granulometric studies in northern Argentine (with a short chapter on the regional geology of central South America)*, Geol. Ann. Stockholm, arg. 18, h. 2, p. 125–213, (incl. geologic map 1:12,500,000).

——— (1936b) *Investigaciones sobre el material clástico en formaciones del Norte Argentino*, Inform. Petrol., Bol. 13 (139), p. 75–120, Buenos Aires.

Halle, Th. G. (1911) *On the geological structure and history of the Falkland Islands*, Geol. Inst. Upsala, Bull. 11.

Halse, G. W. (1937) *The stratigraphy of west Buchivacoa, Venezuela*, 1st Venezuelan Geol. Cong., Geol. Mineral., Bol. Tomo 1, p. 175–184.

Harder, E. C., and Chamberlin, R. T. (1915) *The geology of central Minas Geraes Brazil*, Jour. Geol., vol. 23, p. 341–378, 385–424.

Harrington, H. J. (1942) *A brief summary of early Paleozoic formations and faunas of Argentina*, 8th Am. Sci. Cong., Washington 1940, Pr., vol. 4, p. 69–78.

Harrison, J. B., and Jukes-Browne, A. J. (1890) *The geology of Barbados*, 8 vols., London.

Harrison, J. V. (1940) *A preliminary note on the geology of the central Andes of Peru;* Soc. Geol. Peru (Lima), B. t. 10, 52 pages (Spanish and English) 20 pls. (incl. colored geologic map, 1:253,000).

Hatcher, J. B. (1900) *Sedimentary rocks of southern Patagonia*, Am. Jour. Sci., 4th ser., vol. 9, p. 85–108.

Haupt, O. (1907) *Beiträge zur Fauna des oberen Malm und der unteren Kreide in der argentinischen Kordillere*, Neues Jahrb. Mineral. Geol. Palaont., Beilage Bd. 23.

Heald, K. C., and Mather, K. F. (1922) *Reconnaissance of the eastern Andes between Cochabamba and Santa Cruz, Bolivia*, Geol. Soc. Am., Bull., vol. 33, p. 553–570.

Hedberg, H. D. (1937) *Stratigraphy of the Rio Querecual section in the northeastern Anzoategui, Venezuela*, Bol. Geol. Mineral., t. 1, nos. 2–4, p. 239–250. 2 maps, 1 fig.

——— (1938) *Second Venezuelan Geological Congress, San Cristobal, April 1–7, 1938* (Abstract), Am. Assoc. Petrol. Geol., Bull., vol. 22, p. 1101.

——— (1939) *Trinidad Geological Conference, April 18–27, 1939* (*Abstract*), Am. Assoc. Petrol. Geol., Bull., vol. 23, p. 1238.

——— (1942) *Mesozoic stratigraphy of northern South America*, 8th Am. Sci. Cong., Washington, 1940, Pr., vol. 4, p. 195–227.

——— and Sass, L. C. (1937) *Synopsis of the geologic formations of the western part of the Maracaibo Basin, Venezuela*, Bol. Geol. Mineral. Venezuela, (1st Venezuelan Geol. Cong.), p. 71–112.

Heim, Arnold (1940) *Geological observations in the Patagonian Cordillera*, Eclog. Geol. Helvetiae (Schweiz), Geol. Ges., 33 (1), p. 25–51.

Hettner, A. (1892) *Die Kordillere von Bogotá*, Petermans Mitteil., vol. 22, no. 104, 131 pages, Gotha.,

——— and Linck, G. (1886) *Beiträge zur Geologie und Petrographie der kolumbianischen Anden* Zeitschr. Deutsche Geol. Gesell.

Holdhaus, K. (1925) *Sobre algunos lamellibranchios fosseis do Sul do Brasil*, Serv. Geol. Mineral., Mon. 3.

Hubach, E. (1931) *Exploración en la región de Apulo, San Antonio, Viotá*, Mineral. Petrol., Bol., vol. 4, Bogota.

Huene, F. von (1927) *Beitrag zur Kenntnis mariner mesozoischer Wirbeltiere in Argentinen*, Centralbl. Mineral., Geol., Paläont.

——— (1928) *Überblick über die Schichtenfolge der jüngeren Kreide*, Centralbl. Mineral., Geol., Paläont., Abt. B.

——— (1929a) *Terrestrische Oberkreide in Uruguay*, Centralbl. Mineral., Geol., Paläont.

——— (1929b) *Über Rhynchosaurier und andere Reptilien aus den Gondwana-ablagerungen Süderamerikas*, Geol. Palaeont., Abh., N.F., vol. 17, sec. 1, Jena.

——— (1941) *A idade permiana inferior de todas as camadas contendo mesosaurios* (translated by Gerson de Faria Alvin from *Das unterpermische Alter aller Mesosaurier fuhrenden Schichten*, Zentralbl. Mineral., Abt. B, no. 7, p. 200–210, 1940), Mineracao e Metal., vol. 6, no. 32, p. 64–68.

Iddings, A., and Olsson, A. (1928) *Geology of northwest Peru*, Am. Assoc. Petrol. Geol., Bull., vol. 12, no. 1, p. 1–39.

Ihering, H. von (1905) *Les mollusques fossiles du Tertiaire et du Crétacé supérieur de l'Argentine*, An. Museo Nac. Hist. Natural, vol. 14, Buenos Aires.

——— (1907 *Les mollusques fossiles du Tertiaire et du Crétacé supérieur de l'Argentine*, An. Museo. Nac., vol. 7, Buenos Aires.

——— (1924) *Die Kreide-Eocän-Ablagerungen der Antarktis*, Neues Jahrb. Mineral., Geol., Paläont., Bd. 51, Stuttgart.

Ijzerman, R. (1931) *Outline of the geology and petrography of Surinam* (*Dutch Guiana*). Martinus Nijhoff, The Hague, Holland, 517 p., 48 pls., 63 figs, 6 maps.

Jaworski, E. (1913) *Beiträge zur Kenntnis der Lias-Volen in Südamerikas und Stammesgeschichte der Gattung Vola*, Zeitschr. Paläont., Ges., vol. 1, sec. 2.

——— (1913–1915) *Beiträge zur Kenntnis des Jura in Südamerika*, Neues Jahrb. Mineral., Geol., Paläont., Bd. 37–40.

——— (1922) *Die marine Trias in Sudamerika*, Neues Jahrb. Mineral., Geol., Paläont., vol. 47.

——— (1923) *Die Trias-, Lias-, und Doggerfauna der andinen Geosynklinale und ihre verwandschaftlichen Beziehungen*, Geol. Rundschau, vol. 14.

——— (1925a) *Beiträge zur Kenntnis des Jura in Südamerika, Teil I und II*, Neues Jahrb., Mineral., Geol., Paläont., Bd. 37, 40, Stuttgart, 1913 and 1915. (Versión castellana de esta obra en Nuevas Publicaciones de la Dirección Gral. de Minas Argentina, no. 4, Buenos Aires.

——— (1925b) *Contribución a la palaeontologia del Jurásico sudamericano*, Direc. Gener. de Min., Pub., vol. 4, Buenos Aires.

——— (1926) *Bemerkungen zur Paläontologie un Stratigraphie des argentinischen Oberlias und Unterdogger*, Centralbl. Mineral., Geol., Palaont., Jahrg., Abt. B.

———, Krantz, F., and Gerth, H. (1926) *Lias und Dogger*, Teil I von: *Beiträge zur Paläontologie und Stratigraphie des Lias, Doggers, Tithons und der Unterkreide in den Kordilleren im Süden der Provinz Mendoza* (*Argentinien*), Geol. Rundschau, vol. 17a (Steinmann-Festschrift).

Jones, W. F., and Whitehead, W. L. (1929) *Cretaceous-Eocene unconformity of Venezuela*, Am. Assoc. Petrol. Geol., Bull., vol. 13, p. 617-624, 3 figs.

Jordan, D. S., and Branner, J. C. (1908) *The Cretaceous fishes of Ceará, Brazil*, Smithson. Mis. Coll., no. 1793, vol. 52, p. 1–29.

Juana, C. G. de (1937) *General geology and stratigraphy of the Cumarebo Region, Falcon State*, Geol. Min. (Caracas), Bol., Tomo 1, p. 187–205.

——— (1938) *A contribution to the study of the Zulia-Falcon sedimentary basin, Venezuela*, (2d Venezuelan Geological Congress), Geol. Min., Venezuela, Bol., Tomo 11, p. 123–140.

Jukes-Browne, A. J., and Harrison, J. B. (1891–1892) *The geology of Barbados*, Geol. Soc. London, Quart. Jour., vol. 47, p. 175; vol. 48, p. 170.

Karsten, H. (1856) *Über die geognostischen Verhältnisse des westlichen Columbien, der heutigen Republiken Neu-Granada und Ecuador*, Amtl. Ber. Naturforsch. Ges., Wien.

Katzer, F. (1903) *Grundzüge der Geologie des unteren Amazonasgebietes*, Leipzig, p. 1-296.

Kaye, M. Kamen (1937) *Reconnaissance geology in state of Anzoategui, Venezuela, South America*, Am. Assoc. Petrol. Geol., Bull., vol. 21, p. 233–245.

——— (1938) *Geological succession of central Venezuela*, Am. Assoc. Petrol. Geol., Bull., vol. 22, p. 1224.

Kayser, E. (1878) *Über primordiale und untersilurische Fossilien aus der argentinischen Republik*, Paläont., Suppl. 3.

Kehrer, L. (1937) *Some observations on Cretaceous and pre-Cretaceous beds in the southwestern and northern central parts of Venezuela*, Geol. Min., Bol., Tomo 1, p. 45–70.

——— (1938) *Some observations on the stratigraphy in the states of Tachira and Merida, S. W. Venezuela*, Geol. Min., Bol., Tomo 2, p. 44–55.

——— (1939) *Geology of central Venezuela*, Am. Assoc. Petrol. Geol., Bull., vol. 23, p. 699.

Keidel, H. (1913) *Über das Alter, die Verbreitung und die gegenseitigen Beziehungen der verschiedenen tektonischen Strukturen in den argentinischen Gebirgen*, 12th Inter. Geol. Cong., Toronto, C. R.

——— (1921) *Observaciones geológicas en la Pre-Cordillera de San Juan y Mendoza*, An. Minist. Agric., Buenos Aires, vol. 15, núm. 2, Monographía II.

——— (1922) *Sobre la distribución de los depósitos glaciares del pérmico conocidos en la Argentina*, Acad. Nac. Córdoba, Bol. 25, p. 239-368.

Keidel, J. (1910) *La zona mesozoica en la falda oriental de la cordillera entre el Rio Diamante y el Rio Neuquén Republ.*, Argentina An. Minist. Agric., Sec. Geol., vol. 5, Teil 2.

——— (1916) *La geología de las Sierras de la Provincia de Buenos Aires, y sus relaciones con las montanas de sud Africa y los Andes*, An. Minist. Agric., vol. 11, No. 3, Buenos Aires.

——— (1925a) *Sobre la estructura tectónica de las capas petrolíferas en el oriente del Terr. del Neuquén*, Direc. Gral. de Minas, Pub. 8, Buenos Aires, 67 p., 4 pls.

——— (1925b) *Sobre el desarollo paleogeográfico de las grandes unidades geológicas de la Argentina*, An. Soc. Argentina Estudios Geog. Gaea, vol. 1, no. 4, Buenos Aires.

——— (1927) *Sobre las relaciones geológicas entre la Puna y la Cordillera principal de Los Andes*, Acad. Nac. Cienc. Córdoba, Bol. 30.

——— and Harrington, H. J. (1938) *On the discovery of Lower Carboniferous tillites in the pre-Cordillera of San Juan, west Argentina*, Geol. Mag., vol. 75, p. 103–129, 1 fig., 2 pls.

Knechtel, M. M. (1938) *Pre-Cretaceous rocks in the state of Barinas, Venezuela*, Bol. Geol. Min., Caracas, Venezuela, t. 2, no. 2–3–4, p. 182–186.

Kozlowski, R. (1923) *Faune dévonienne de Bolivie*, An. de Paléaont. T. 12, fasc. 1–2, Paris.

——— (1930) Andobulus *gen. nov. et quelques autres brachiopodes inarticulés de l'Ordovicien de Bolivie*, Serv. Géol. de Pologne, Bul. 6, Varsovie.

Krantz, F. (1928) *La Fauna del Tithonio superior y medio de la Cordillera argentina en la parte meridional de la Provincia de Mendoza*, Actas Acad. Nac. Cienc. Córdoba, vol. 10, entrega 1a.

Kugler, H. G. (1936) *Summary digest of geology of Trinidad*, Am. Assoc. Petrol. Geol., Bull., vol. 20, p. 1439.

——— (1938) *The Eocene of the Soldado rock near Trinidad*, Geol. y Minas Caracas, Bol., Tomo 2, nos. 2, 3, 4, p. 202–225.

Kundig, E. (1938) *The Pre-Cretaceous rocks of the central Venezuelan Andes with some remarks about the tectonics*, Geol. Min. Venezuela, Bol., Tomo 2, p. 21–43.

Kurtz, R. G. (1921) *Atlas de plantas fósiles de la República Argentina*, (*Obra póstuma de acuerdo con los manuscritos editada por C. C. Hosseus*), Actas Acad. Nac. Cienc. Córdoba, vol. 7, p. 129–153.

Lehner, M. E. (1935) *Geology of the petroliferous areas of South America and the Islands of the Caribbean Archipelago. I. Trinidad*, Ann. des Comb. Liqu., vol. 10, no. 4, p. 692.

Leinz, Viktor; Barbosa, Alceu Fabio, and Teixeira, Emilio Alves (1941) *Mapa geológica Caçapava-Lavras, Brazil, Rio Grande do Sul.*, Dir. Prod. Mineral., Pub. no. 6, Bol. 90, 39 pages, 5 figs., colored geologic map, 1:50,000.

Leme, A. B. P. (1924) *Evolução da estructura da terra e geologia do Brazil*, Mus. Nac., Rio de Janeiro.

Liddle, R. A. (1927) *Tectonics of the Maracaibo Basin, Venezuela*, Am. Assoc. Petrol. Geol., Bull., vol. 11, p. 177.

——— (1928) *The geology of Venezuela and Trinidad*, Fort Worth, Texas, J. P. MacGowan.

Lisboa, M. A. R. (1914) *The Permian geology of northern Brazil*, Am. Jour. Sci., 4th ser., vol. 37, p. 425–443.

Lisson, C. I. (1907) *Contribución a la geología de Lima y sus Alrededores*, Lima, Gil. 125 p., 27t. 2 maps.

——— (1908) *Contribución al conocimiento sobre algunos ammonites del Peru*, Lima, 66 p., 23t., 20 Text figs., 4th Cong. Cient. Latino Americano, Santiago de Chile.

——— (1913–1914) *Edad de los fósiles peruanos y distribución de sus depósitos en la República.* (1) Ubicación de afloremientos sincrónicos y sinopsis de su fauna y flora fósiles, 1913. (2) Fauna y flora pertenecientes a cada uno de los pisos geológicos 1 mapa paleontológico.

——— (1926) *Apéndice a la obra "Edad de los Fósiles Peruanos y Distribución de sus depósitos en toda la república"*, Soc. Geol. Peru, Bol. 2, p. 41–46.

——— and Boit, B. (1924) *Edad de los Fósiles Peruanos y distribución de sus depósitos*, 3d ed., Lima Imprente Americana, p. 1–226, 1 map.

Lopez, Victor M., Mencher, E., and Brineman, J. H., Jr. (1942) *Geología del Sureste de Venezuela*, *Revista de Fomento*, Geol. Soc. Am., Bull., vol. 53, p. 849-872.

MacKenzie, A. N. (1937) *The geologic section of the Barinas Region; Districts of Barinas, Bolivar and Obispos, State of Zamora, Venezuela*, Geol. Min. Venezuela. Bol., t. 1, nos. 2–4, p. 267–283.

Marsters, V. F. (1921) *Outline of the geology and development of the petroleum fields of Peru, South America, with notes on other occurrences in the Peruvian Republic*, Am. Assoc. Petrol. Geol., Bull., vol. 5, p. 585–604, 1 map, 2 figs.

Mather, K. F. (1922) *Front ranges of the Andes between Santa Cruz, Bolivia and Embarcación, Argentina*, Geol. Soc. Am., Bull., vol. 33, p. 703–764.

Maury, C. J. (1929) *The fossiliferous limestone at Bom Jesus de Lapa, Bahia*, Ebda.

——— (1912) *A contribution to the paleontology of Trinidad*, Acad. Nat. Sci. Philadelphia, Jour., 2d ser., vol. 15, p. 25–112.

——— (1925) *A further contribution to the paleontology of Trinidad-Miocene horizons*, Bull. Am. Paleont., vol. 10, no. 42. 250 p.

——— (1927) *Fosseis silurianos de Santa Catharina*, Serv. Geol. Brazil, Bol. 23, Rio de Janeiro.

——— (1934) *Fossil invertebrata from northeastern Brazil*, Am. Mus. Nat. Hist., Bull., vol. 67.

Maycock, J. D. (1821) *Geological description of Barbados with a map of the island*, Sci. Lit. Arts., Quart. Jour., vol. 11, p. 10.

McLaughlin, D. H. (1924) *Geology and physiography of the Peruvian Cordillera, Depts. of Junin and Lima*, Geol. Soc. Am., Bull., vol. 35, p. 591–632.

——— (1925) *Notas sobre la Geología y Fisiografía de los Andes Peruanos en el departamento Norte de Santander*, Minas Petrol. (Colombia), Bol., p. 79–84, 237–253. (July, Dec.)

Miller, B. L., and Singewald, J. T. (1919) *Mineral deposits of South America*, McGraw-Hill Book Co., New York, 598 pages.

Moraes Rego, L. F. de (1926) *Reconnecimento geol. da parte occidental do Estado da Bahia*, Serv. Geol. Brazil, Bol. 17, Rio de Janeiro.

——— (1930) *Geologia do petroleo no estado de Sao Paulo*. Serv. Geol. Brazil, Bol. 46.

Moricke, W. (1894) *Die Versteinerungen des Lias und Unteroolith von Chile*, Neues Jahrb. Mineral., Geol., Paläont., Bd. 9, Stuttgart.

Neumann, R. (1907) *Beiträge zur Kenntnis der Kreideformation in Mittelperu*, Neues Jahrb. Mineral., Geol., Paläont., Bd. 24.

Newell, N. D. (1946) *Geological investigations around Lake Titicaca*, Am. Jour. Sci., vol. 244, p. 357–366.

Nordenskjold, E. (1905) *Exploration scientifique au Pérou et en Bolivie (1904–1905)*, La Géographie, vol. 12, p. 289–296.

Oliveira, A. I. de (1925) *Atravaz da Guyana Brasileira pelo Rio Erepecuru estado do Para*, Serv. Geol. Min. Brazil, Bol. 31.

——— (1937) *Recursos mineraes da bacia do Rio Branco (Estado do Amazonas), Brazil*, Serv. Fom. Prod. Min., Avulso no. 18, 12 pages, 4 figs., 2 pls, 1937. Reprinted from Min. Met. (Rio de Janeiro) 1 (6), p. 243–250, March–April.

——— (1938) *Mappa geológico do Brazil e de parte dos paizes visinhos, Scale 1/7,000.000, Brazil*, Serv. Fom. Prod. Mineral.

Oliveira, Euzebio P. de (1915) *Geologia*, Exped. scient. Roosevelt-Rondon, Annexo I, Geologia Rio de Janeiro. (Estrado de Ferro Madeira-Mamoré, Paginas 61-65)

——— (1918) *Regiões carboniferas dos Estados do Sul*, Serv. Geol. Min. Brazil Mon. em 8°, 125 p., various maps, Rio de Janeiro.

——— (1927) *Geologia e recursos minerais do estado de Paraná*, Serv. Geol. Min. Brazil, Mon. 4 (with geological map).

Olsson, A. A. (1934) *Contributions to the paleontology of northern Peru. The Cretaceous of the Amotape region*, Bull. Am. Paleont., vol. 20.

——— (1939) *Introduction to the geology of northwest Peru and southwest Ecuador*, Ann. Off. Combust. Liq., vol. 14, p. 551.

——— (1944) *Contributions to the paleontology of northern Peru; Part VII, The Cretaceous of the Paita region*, Bull Am. Paleont., vol. 28, no. 111, 112 pages, 3 figs., 17 pls.

——— and Caster, Kenneth E. (1937) *Devonian fauna from Colombia Abstract*, Geol. Soc. Am., Pr. 1936, p. 369–370.

——— and Iddings, A. (1928) *Geology of northwest Peru*, Am. Assoc. Petrol. Geol., Bull., vol. 12, p. 1.

Oppenheim, V. (1935) *Petroleum geology of Gondwana rocks of southern Brazil*, Am. Assoc. Petrol. Geol., Bull., vol. 19, p. 1725-1805, 15 figs., 1 map.

——— (1936a) *Geology of Devonian areas of Parana Basin in Brazil, Uruguay and Paraguay*, Am. Assoc. Petrol. Geol., Bull., vol. 20, p. 1208–1236, 6 figs., 1 map.

——— (1936b) *Some aspects of a geological exploration for oil in the upper Amazon*, Oil Weekly, Vol. 82, p. 44, July 20.

——— (1937) *Contribution to the geology of the Venezuelan Andes*, Geol. Min., Bol. (Venezuela, Serv. Tecn. Min. y Geol.) t. 1, nos. 2, 4, p. 23–45. 2 figs., 1 pl.

——— (1940) *Jurassic-Cretaceous (Girón) beds in Colombia and Venezuela*, Am. Assoc. Petrol. Geol., Bull., vol. 24, p. 1611–1619.

——— (1941) *Geología del sur de la Cordillera Oriental entre los Llanos y el Magdalena, Colombia*, Acad. Colombia Rev. Vol. 4, no. 14, p. 175–181, Jan.–July, *See also* Bol. Minas y Petrol. (Bogota) (no. 121–144) p. 81–94, 3 pls. (inc. geol. map, 1:238,000).

Paiva Teixeira, Glycon de (1929) *Valle do rio Negro*, Serv. Geol. Min. Brazil, Bol. 40.

——— (1940) *Considerações sobre a transgressão cárnica na America do Sul, Brazil*, Div. Geol. Min., Bol. 98, p. 23–30, map.

Paulcke, W. (1903) *Über die Kreideformation in Südamerika und ihre Beziehungen zu anderen Gebieten*, Neues Jahrb., Mineral., Geol., Paläont., Bd. 17.

——— (1907) *Die Cephalopoden der oberen Kreide Südpatagoniens*, Ber. Naturforsch. Ges. Freiburg, vol. 15.

Piatnitzky, Alejandro (1933) *Retico y liásico en los valles de los ríos Genua y Tecka y sedimentos continentales de la sierra de San Bernardo*, Inform. Petrol., Buenos Aires, Bol., an. 10, no. 103, p. 151–182.

——— (1936) *Estudio geológico de la region del Rio Chubut y del Rio Genua*, Inform. Petrol, Buenos Aires, Bol., an. 13, no. 137, p. 83–118.

——— (1938) *Observaciones geológicas en el oeste de Santa Cruz (Patagonia)*, Inform. Petrol., Buenos Aires, Bol. 15, no. 165, p. 45–95.

Pilsbry, H. A., and Olsson, A. A. (1935) *Tertiary freshwater mollusks of the Magdalena embayment, Colombia*, Acad. Nat. Sci., Philadelphia, vol. 87, p. 21.

Quensel, P. D. (1910) *Beitrag zur Geologie der patagonischen Cordillera*, Geol. Rundschau, vol. 1.

——— (1911) *Geologisch-petrographische Studien in der patagonischen Cordillera*, Geol. Inst. Upsala, Bull., vol. 11.

Rassmuss, J. (1920) *Geología de los yacimientos de carbón en la república argentina*, Direc. Gen. de Minas, Bol. 23, Buenos Aires.

Reed, F. R. C. (1927) *Upper Carboniferous fossils from Argentina*, Carnegie Inst. Washington, Pub. 381, Append.

——— (1929a) *Faunas triásicas do Brazil*, Serv. Geol. Mineral. Brazil, Mon. 6, Rio de Janeiro.

——— (1929b) *Novos Phyllopodos fosseis do Brazil*, Serv. Geol. Brazil, Bol. 34, Rio de Janeiro.

——— (1930) *Una nova fauna permo-carbonifera do Brasil*, Serv. Geol. Brasil, Mon. 10, Rio de Janeiro.

Renz, H. H. (1942) *Stratigraphy of northern South America, Trinidad and Barbados*, 8th Am. Sci. Cong., Washington, Pr., vol. 4, p. 513–572.

Rich, J. L. (1942) *Structure and physiography of the western Andes*, 8th Am. Sci. Cong., Washington, Pr., vol. 4, p. 391–392.

Richter, M. (1925) *Beiträge zur Kenntnis der Kreide in Feuerland*, Neues Jahrb. Mineral., Geol., Palaont., Bd. 52, Abt. B, Stuttgart.

Rigal, R. (1930) *El Liásico en la cordillera del Espinazito (Prov. de San Juan)*, Direc. Gen. de Minas, Pub., vol. 74, Buenos Aires.

Riggs, Elmer S. (1936) *Stratigraphy of the Araucanian formation (Pliocene) Patagonia, Argentina* (Abstract), Geol. Soc. Am., Pr. 1935, p. 402–403.

Ruedemann, R. (1929) *Fossils from the Permian tillite of São Paulo, and their bearing on the origin of the tillite* (Abstract), Geol. Soc. Am., Bull., vol. 40, p. 243.

Rutten, L. (1931a) *On rocks from the Caribbean Coast Range, northern Venezuela, between Puerto Cabello-La Cumbre and between La Quira-Caracas*, Kon. Acad. Wetensch, Pr., vol. 34, p. 1013–1022, Amsterdam.

——— (1931b) *On rocks from the Venezuelan Islands between Bonaire and Trinidad and on some rocks from northwestern Venezuela*, Kon. Acad. Wetensch., Pr., vol. 34, p. 1101–1110, Amsterdam.

Sapper, Carl (1906) *Über Gebirgsbau und Borden des südlichen Mittelamerika*, Petermanns Mitt., Erganzungsband, vol. 32.

Schaub, H. P. (1944) *Fusulinids in La Quinta formation, Venezuela*, Am. Assoc. Petrol. Geol., Bull., vol. 28, p. 1642–1644.

Schiller, W. (1912) *La alta Cordillera de San Juan y Mendoza*, Am. Minist. Agric., vol. 7, no. 5., Buenos Aires.

——— (1922) *Los sedimentos marinos del límite entre el Cretáceo y Terciario de Roca en la Patagonia septentrional*, Rev. Mus. La Plata, vol. 26.

Schlagintweit, O. (1937) *Stratigraphic observations in North Argentina*, Inform. Petrol. (B.A.), Bol., vol. 14, no. 156, p. 1-49, 24 figs.

——— (1941) *Correlación de las calizas de Miraflores en Bolivia con el horizonte Calcareo-dolomitico del Norte Argentino*, Inst. Mus., Univ. La Plata, tomo 6, Geologia no. 14, p. 337–354, 9 figs. and geologic map, Argentina.

Schomburgk R. H. (1848) *The history of Barbados, comprising a geographical and statistical description of the Island, a sketch of the historical events since the settlement, and an account of its geology and natural productions*, 8 volumes, London.

Schuchert, Charles (1916) *Fossil determinations* in Bowman: Appendix B, p. 321 of *The Andes of southern Peru*, Henry Holt and Co.

——— (1928a) *The so-called "Lower Silurian" fossils of Venezuela*, Am. Assoc. Petrol. Geol., Bull., vol. 12, p. 951–952.

——— (1928b) *The continental displacement hypothesis as viewed by Du Toit*, Am. Jour. Sci., 5th ser., vol. 16, p. 266–274.

——— (1935) *Historical geology of the Antillean Caribbean region or the lands bordering the Gulf of Mexico and the Caribbean Sea*, JohnWiley & Sons, New York, 811 p.

Schurmann, H. M. E. (1934) *Rock formations in the Venezuelan Andes*, Neues Jahrb. Mineral., Geol., Palaont., Bd. 68, Abt. A, p. 377.

Scott, William Berryman (1942) *The Later Cenozoic mammalian faunas of South America*, 8th Am. Sci. Cong., Washington, 1940, Pr., vol. 4, p. 333–357.

Senn, A. (1940) *Paleogene of Barbados and its bearing on history and structure of the Antillean-Caribbean region*, Am. Assoc. Petrol. Geol., Bull., vol. 24, p. 1545–1610.

Sheppard, G. (1927) *Observations on the geology of the Santa Elena Peninsula, Ecuador, South America*, Inst. Petrol. Technol., Jour., vol. 13, p. 424.

——— (1929) *The age of the Guayaquil limestone*, Am. Assoc. Petrol. Geol., Bull., vol. 13, p. 383.

——— (1930) *Geology of southwest Ecuador*, Am. Assoc. Petrol. Geol., Bull., vol. 14, p. 263.

——— (1933) *Outlines of Ecuadorian geology*, Pan.-Am. Geol., vol. 59, p. 115.

Siemiradzki, J. V. (1898) *Geologische Reisebeobachtungen in Süd-brasilien*, Sitz.-Ber. Akad., Wien. Mat.-nat. Bd. 107, Abs. 1, p. 23-39.

Sievers, W. (1888a) *Sierra de Santa Marta und die Sierra de Perija*, Zeitschr. Gesell. Erdkunde, vol. 28, Berlin.

——— (1888b) *Die Kordillere von Merida nebst Bemerkungen über das Karibische Gebirge* Geog. Abhandl., Bd. 3, Heft 1, 288 p. Vienna, 1 map-15 pl..

——— (1896) *Zweite Reise in Venezuela*, Mittl. Geog. Ges. Hamburg, Bd. 12, 327 p., 2 maps, Hamburg.

Simpson, George Gaylord (1941) *The Eocene of Patagonia*, Am. Mus. Nat. Hist., Novit. no. 1120, 15 pages.

——— (1942) *Early Cenozoic mammals of South America*, 8th Am. Sci. Cong., Washington, 1940, Pr., vol. 4, p. 303–332.

Singewald, J. T., Jr. (1927) *Pongo de Manseriche*, Geol. Soc. Am., Bull., vol. 38, p. 479–492, 9 figs.

——— (1937) *Geological exploration between Upper Jurua River, Brazil, and Middle Ucayali River, Peru*, Am. Assoc. Petrol. Geol., Bull., vol. 21, p. 1347.

Sinclair, J. H. (1924) *Geology of Guayaquil, Ecuador, South America*, Am. Jour. Sci., 5th ser., vol. 7, p. 491–497.

——— and Berkey, C.P. (1923) *Cherts and igneous rocks of the Santa Elena oil field, Ecuador*, Chem. Abst., vol. 17, p. 309; Min. Metall., vol. 4, p. 424.

Sommermeier, L. (1910) *Die fauna des Aptien und Albien im nordlichen Peru, I. Cephalopoden*, Beitr. Geol. Pal. Südamerika 15, Neues Jahrb. Mineral., Geol., Paläont., Bd. 30, p. 313–382.

Stanton, T. W. (1901) *The marine Cretaceous invertebrates*, in *Reports of the Princeton University Expeditions to Patagonia, 1896-1899*, vol. 14, no. 1, Princeton, N. J. and Stuttgart.

Stappenbeck, R. (1910) *La Precordillera de San Juan y Mendoza*, An Minist. Agric., Sec. Geol., vol. 4, no. 3, p. 1–187, Buenos Aires.

——— (1917) *Geologia de la falda oriental de la Cordillera del Plata (Prov. de Mendoza)*, An. Minist. Agric., Sec. Geol., vol. 12, no. 1, Buenos Aires.

——— (1924) *Geologie des Chicamatales in Nordperu und seiner Anthrazillagerstatten*, Geol. Paläont., Abh., N. F., 16, Jena.

——— (1927) *Über Transgressionen und Regressionen des Meeres und Gebirgsbildung in Südamerika*, Neues Jahrb. Mineral., Geol., Paläont., Bd. 58, p. 453–496.

Stehn, E. (1923) *Beiträge zur Kenntnis des Bathonien und Callovien in Südamerika*, Neues Jahrb. Mineral., Geol., Paläont., Bd. 49, Stuttgart.

Steinmann, G. (1881a) *Über Tithon und Kreide in den peruanischen Anden*, Neues Jahrb. Mineral., Geol., Paläont., Bd. 1.

——— (1881b) *Über Tithon und Kreide in den peruanischen Anden*, Neues Jahrb. Mineral., Geol., Paläont., Bd. 2.

——— (1882) *Über Jura und Kreide in den peruanischen Anden*, Neues Jahrb, Mineral., Geol., Paläont., Bd. 1.

——— (1910) *Gebirgsbildung und Massengesteine in der Kordillere Südamerikas*. Geol. Runschau, Bd. 1.

——— (1929) *Geologie von Peru*, p. 1–448, Heidelberg.

——— and Hoek, H. (1912) *Das Silur und Kambrium des Hochlandes von Bolivien und ihre Fauna*, Neues Jahrb. Mineral., Geol., Paläont., Bd. 34.

——— — Lisson, C. (1924a) *Geologische Karte der Kordillere von Peru* (Nach den Beobachtungen von G. Steinmann, C. Lisson, R. Stappenbeck und Anderen entworfen), Carl Winter. Heidelberg.

——— — ——— (1924b) *Mapa geológico de la Cordillera del Peru* (Segun las observaciones de los Señores G. Steinmann, C. Lisson, R. Stappanbeck y otros bosque jado), Carl Winter, Heidelberg.

——— — Wilckens, O. (1908) *Kreide und Tertiärfossilien aus den Magellansländern, gesammelt von der Schwed. Exp. 1895-97*, Arkiv. Zool., vol. 4, Upsala and Stockholm.

———, Deecks, W., and Moricke, W. (1895) *Das Alter und die Fauna der Quiriquina-Schichten*, Neues Jahrb. Mineral., Geol., Paläont., Bd. 16.

———, Hoek, H., and Bistram, A. von (1904) *Zur geologie des südöstlichen Boliviens*, Centralbl., Mineral., Geol., Paläont., Stuttgart, Bd. 5, p. 1-4.

Steuer, A. (1924) *Argentinische Juraablagerungen. Ein Beitrag zur Kenntnis der Geologie und Paläontologie der argentinischen Anden*, Paläont. Abh. VII, (Neue Folge III), Jena, 1897. (Versión castellana en Actas Acad. Nac. Cienc., Córdoba, vol. 7).

Stille, H. (1907) *Geologische Studien im Gebiet des Rio Magdalena, V. Koenen-Festschrift, Stuttgart.*

——— (1939a) *Kordillerisch-atlantische Wechselbeziengungen*, Geol. Rundschau, Bd. 30, H. 3–4, 8 figs., p. 315–342 (Relation between the folding of the Cordilleran region of the Americas and the origin of the Atlantic ocean basin).

——— (1939b) *Queratlantische Faltenverbindungen*, Geol. Rundschau, Bd. 30, H. 3–4, p. 343–345 (Discusses relations of Alpine and Variscan folding on the east side of the Atlantic ocean basin and folding on the western side of the basin).

Suess, E. (1885–1909) *Das Antlitz der Erde*, I, p. 660, 665, 666, 668, 671, 677, 683, 684, 689, 693, 752, 767, 772, II/1, p. 202, 326, 328, 654, 655, 661, 679, II/2, p. 531, 538, III, Wien, Leipzig.

Sutton, F. A. (1946) *Geology of the Maracaibo Basin, Venezuela*, Am. Assoc. Petrol. Geol., Bull., vol. 30, no. 10, p. 1621–1741.

Thomas, H. D. (1928–1930) *An upper Carboniferous fauna from the Amotape Mountains, northwestern Peru*, Geol. Mag., vol. 65, 1928: vol. 67.

——— (1935) *On some sponges and a coral of Upper Cretaceous age from Toco Bay, Trinidad*, Geol. Mag., vol. 62, p. 175.

Tilmann, N. (1917) *Die Fauna des unteren und Mittleren Lias in Nord-und Mittel-Peru*, Neues Jahrb, Mineral., Geol., Paläont., Bd. 41.

Toit, A. L. du (1927) *A geological comparison of South America with South Africa*, Carnegie Inst. Washington, Pub. 381.

Tomalin, W. G. C. (1938) *The stratigraphy of the Cretaceous formations in the neighborhood of the Rio Carache, State of Trujillo, Venezuela*, 2d Venezuelan Geol. Cong., Bol. Geol. Min., Tomo II, p. 11–20.

Tornquist, A. A. (1898) *Der Dogger am Espinazito Pass, nebst einer Zusammenstellung der jetzigen Kenntnis von der argentinischen Juraformation*. Paläont. Abh., Dames, Koken, n.f. 4, H. 2. (Version castellana en Actas Acad. Nac. Cienc. Córdoba, vol. 8, 1925).

Trechmann, C. T. (1925) *The Northern Range of Trinidad*, Geol. Mag., vol. 62, p. 544.

——— (1935) *Fossils from the Northern Range of Trinidad*, Geol. Mag., vol. 72, p. 166.

Troll, C., and Finsterwalder, R. (1936) *Die Karten der Cordillera Real und des Talkessels von La Paz (Bolivien) und die Diluvialgeschichte der zentralen Anden*, Peterm. Geog. Mitt. 81, (9–10,12) p. 393–399, Nov. 445–455, Dec. 1935. (Maps 1:50,000 and 1:115,000); Abstract in Geol. Zentralbl., 56 (7), p. 451–452.

Trumpy, D. (1943) *Pre-Cretaceous of Colombia*, Geol. Soc. Am., Bull., vol. 54, p. 1281–1304.

Vaughan, T. W. (1908) *La Minerta en el Peru*, Pub. Min. Fom., Direc. Fom., Lima, KLI y 365 pages, 51 lam.

Walther, K. (1927) *Die Erbohrung von fossilführendem Devon in Uruguay*, Centralbl. Mineral., Geol., Paläont.,

——— (1928) *Nota sobre algunos resultados de la investigación geol. del pais*, Rev. Fac. Agronom, 1, Montevideo.

Waring, G. A. (1926) *The geology of the island of Trinidad, with notes on the paleontology by G. D. Harris*, Johns Hopkins Univ., Stud., Geol. no. 7, Baltimore.

Washburne, C. W. (1929) *State of Sao Paulo, Brazil*, Am. Assoc. Petrol. Geol., Bull., vol. 13, p. 1215.

Wasson, T., and Sinclair, J. H. (1927) *Geological explorations east of the Andes in Ecuador*, Am. Assoc. Petrol. Geol., Bull., vol. 11, p. 1253–1281, pls. 9–11, 4 figs.

Weaver, C. E. (1927) *The Roca formation in Argentina*, Am. Jour. Sci. 5th ser., vol. 13, p. 417–434.

——— (1931) *Palaeontology of the Jurassic and Cretaceous of west central Argentina*, Univ. Wash., Mem. 1, Seattle.

——— (1941) *A general summary of the Mesozoic of South America and Central America*, 8th Am. Sci. Cong., Washington, Pr., vol. 4, p. 149–193, 2 pls. 1 fig., (Paleogeographic map and correlation chart).

Weisbord, N. E. (1926) *Venezuelan Devonian fossils*, Bull. Am. Paleont., vol. 11, no. 46, p. 223.

Wellhofer, B. (1936) *Geology of the west margin of the Argentine Chaco*, Deutsch. Geol. Gesell., vol. 88, p. 557.

Welter, O. (1913) *Eine Tithonfauna aus Nord-Peru*, Beiträge Geol. Paläont S. America Neues Jahrb. Mineral., Geol., Paläont., vol. 1, p. 28–42.

Werenfels, A. (1927) *Geology of the Illescas region, northern Peru (S. A.)*, Eclog. geol. Helvetiae, 20, T. 17, p. 473–486, 4 figs.

Wetzel, W. (1930) *Die Quiriquina-Schichten als Sediment und paläontologisches*, Arch. Paläont., 78, Stuttgart.

Wheeler, O. C. (1935) *Tertiary stratigraphy of the Middle Magdalena Valley*, Acad. Nat. Sci. Philadelphia, vol. 87, p. 21.

White, C. A. (1888) *Contributions to the paleontology of Brazil, comprising description of Cretaceous invertebrate fossils mainly from the provinces of Sergipe, Pernambuco, Para and Bahia*, Arch. Mus. Nac., Rio de Janeiro, vol. 7.

White, D. (1908) *Fossil flora of the Coal Measures of Brazil*, in *Final report of the Brazilian Coal Commission*, Rio de Janeiro.

White, I. C. (1908) *Report of the Brazilian Coal Commission*, Rio de Janeiro.

Wichmann, R. (1921) *Estudio geológico de la zona de reserva de la explotación Nac. de Petroleo de Comodoro Rivadavia*, Direc. Gen. Minas, Bol. 25-B, Buenos Aires.

——— (1928) *Contribución a la geologia de los departmentos Chicalco y Puelen de la parte oriental de la Pampa Central*, Direc. Gen. Minas, Pub. 40, Buenos Aires.

——— (1934) *Contribución al conocimiento geológico de los territorios del Neuquen y del Rio Negro, Argentina*, Direc. Minas Geol., Bol., 39, 27 pages (includes color plates and colored geologic map, 1:200,000).

Wiedenmayer, C. (1937a) *Geology of the Carbonaceous deposits of Coro, State of Falcon*, Geol. Min., Bol., vol. 1, no. 1, p. 65.

——— (1937b) *Comparison of Maturin and Maracaibo sedimentary basin, Venezuela*, 2d Venezuelan Geol. Cong., Geol. Min. Venezuela, p. 221-250.

Wilckens, O. (1904a) *Über Fossilien der Oberen Kreide Südpatagoniens*, Centralbl. Mineral., Geol., Paläont.

——— (1904b) *Revision der Quiriquina-Schichten*, Neues Jahrb, Mineral., Geol., Paläont., Beilbd. 18.

——— (1905) *Die Meeresablagerungen der Kreide-und Tertiär-formation in Patagonien*, Neues Jahrb. Mineral., Geol., Paläont., Beilbd. 21, Stuttgart.

Windhausen, A. (1914) *Contribución al conocimiento geológico de los territorios del Rio Negro y Neuquén*, An. Minist. Agric., Sec. Geol., vol. 10, no. 1, Buenos Aires.

——— (1918a) *Lineas generales de la estratigrafia del Neocomiano en la Cordillera Argentina*, Acad. Nac. Cienc. Córdoba, Bol., vol. 23.

——— (1918b) *The problem of the Cretaceous-Tertiary boundary in South America and stratigraphic position of the San Jorge formation in Patagonia*, Am. Jour. Sci., 4th ser., vol. 44, p. 1-53.

——— (1921) *Informe sobre un viaje de reconocimiento geológico en la parte Nordeste del Territorio del Chubut, Con un estudio petrográfico de algunas rocas, por R. Beder*, Dir. Gen. Minas, Bol. 24 B, Buenos Aires.

——— (1924) *Lineas generales de la constitución geológica de la región situada al oeste del Golfo de San Jorge*, Acad. Nac. Cienc. Córdoba, Bol., vol. 27., p. 167–320.

——— (1931) *Geologia Argentina. Geologia Historica y Regional del Territorio Argentino*, Jacob Peuser, Ltd., Buenos Aires.

——— (1935) *Apuntes sobre la zona petrolera la Patagonia meridional*, Inform. Petrol., Bol. 12, (131), p. 69–79, Buenos Aires.

Wolf, Th. (1892) *Geografia y geologia del Ecuador*, Leipzig.

Woodring, W. P. (1927) *Marine Eocene deposits on the east slope of the Venezuelan Andes*, Am. Assoc. Petrol. Geol., Bull., vol. 11, no. 9, p. 992.

Woods, H., Vaughan, T. W., and Cushman, J. A. (1922) *Geology of the Tertiary and Quaternary periods in the northwest part of Peru*, Macmillan & Co., London.

Woodward, A. Smith (1897) *On a new specimen of the Mesosaurian reptile* Stereosternum tumidum, Geol. Mag., vol. 4.

Wordworth, J. B. (1912) *Geological expedition to Brazil and Chile,* Harvard Coll., Mus. Comp. Zool., Bull., vol. 56, Cambridge, Massachusetts.

Zuber, R. (1890) *Estudio geológico del Cerro de Cacheuta,* Acad. Nac. Cienc. Córdoba, Bol., vol. 10.

Zuloaga, G. (1937) *General geological report on the oilfields of Venezuela,* Cong. Mond. Petrole, vol. 1, sec. 1, p. 319.

——— and Tello B. Manuel (1939) *Exploración preliminar de la Sierra de Imataca, Venezuela,* Min. Fom., Rev. 3 (19), p. 397–439.

Chief Research Geologist, Standard Oil Company, (New Jersey), Room 2150, 30 Rockefeller Plaza, New York 20, N. Y.

Manuscript Received by the Secretary of the Society, November 15, 1946.

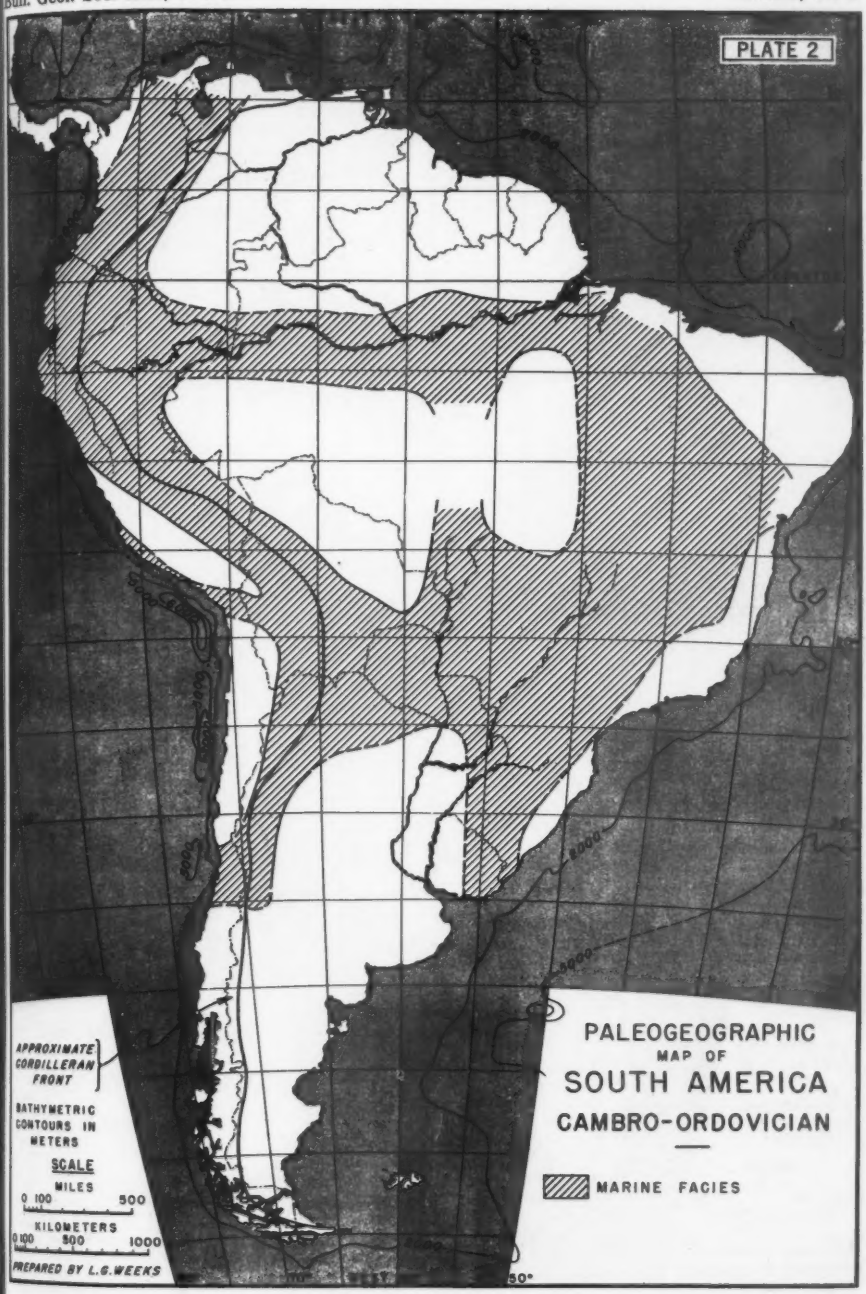


PLATE 2
APPROXIMATE CORDILLERAN FRONT
BATHYMETRIC CONTOURS IN METERS
SCALE
MILES
0 100 500
KILOMETERS
0 100 500 1000
PREPARED BY L.G.WEEKS
PALEOGEOGRAPHIC
MAP OF
SOUTH AMERICA
CAMBRO-ORDOVICIAN
MARINE FACIES
2000
4000
6000
50°

PLATE 3
APPROXIMATE CORDILLERAN FRONT
BATHYMETRIC CONTOURS IN METERS
SCALE
MILES
0 100 500
KILOMETERS
0 100 500 1000
PREPARED BY L.G.WEEKS
PALEOGEOGRAPHIC MAP OF SOUTH AMERICA
SILURIAN
MARINE FACIES
1000
2000
3000
50°

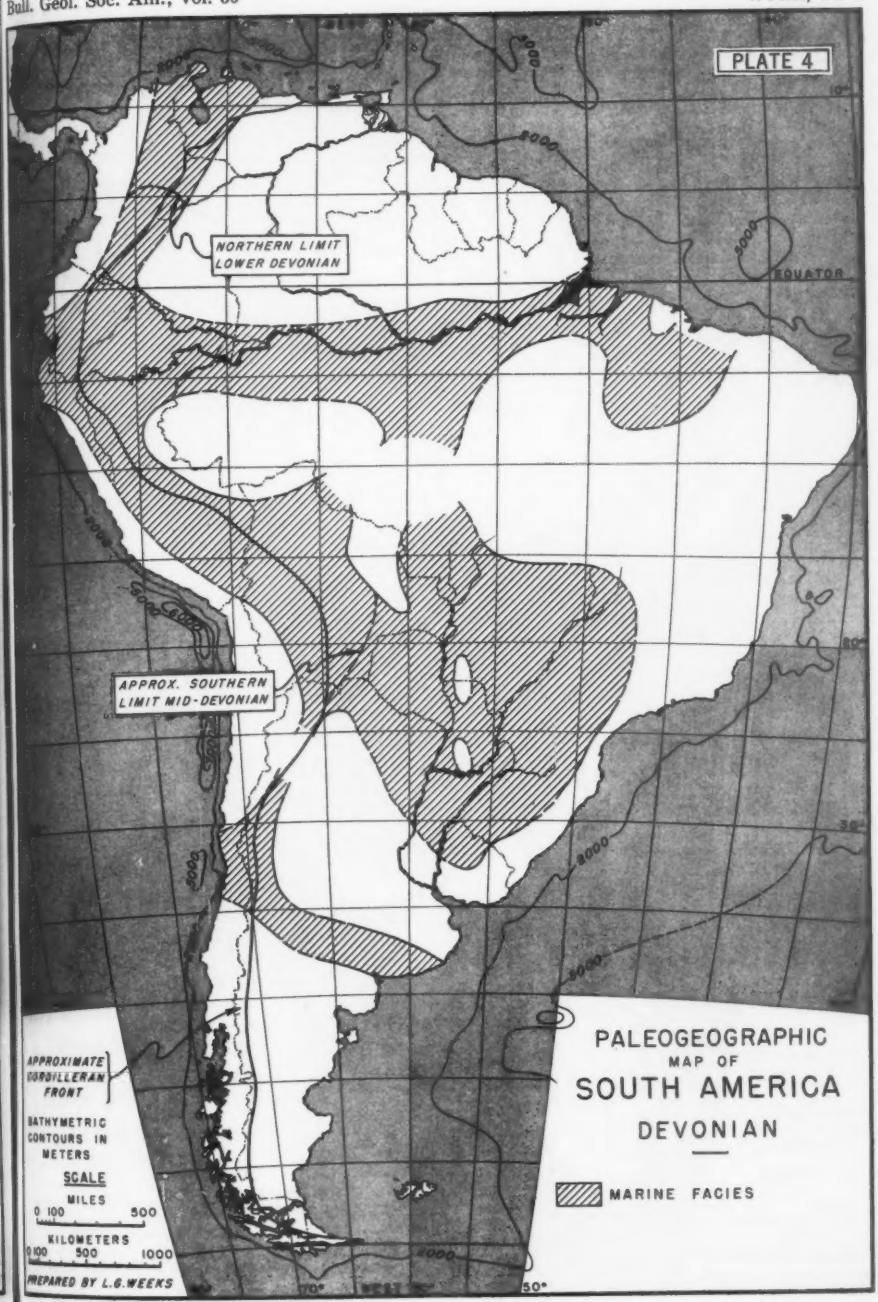


PLATE 4
NORTHERN LIMIT LOWER DEVONIAN
APPROX. SOUTHERN LIMIT MID-DEVONIAN
EQUATOR
APPROXIMATE CORDILLERAN FRONT
BATHYMETRIC CONTOURS IN METERS
SCALE
MILES
0 100 500
KILOMETERS
0 100 500 1000
PREPARED BY L.G. WEEKS
PALEOGEOGRAPHIC MAP OF SOUTH AMERICA DEVONIAN
MARINE FACIES

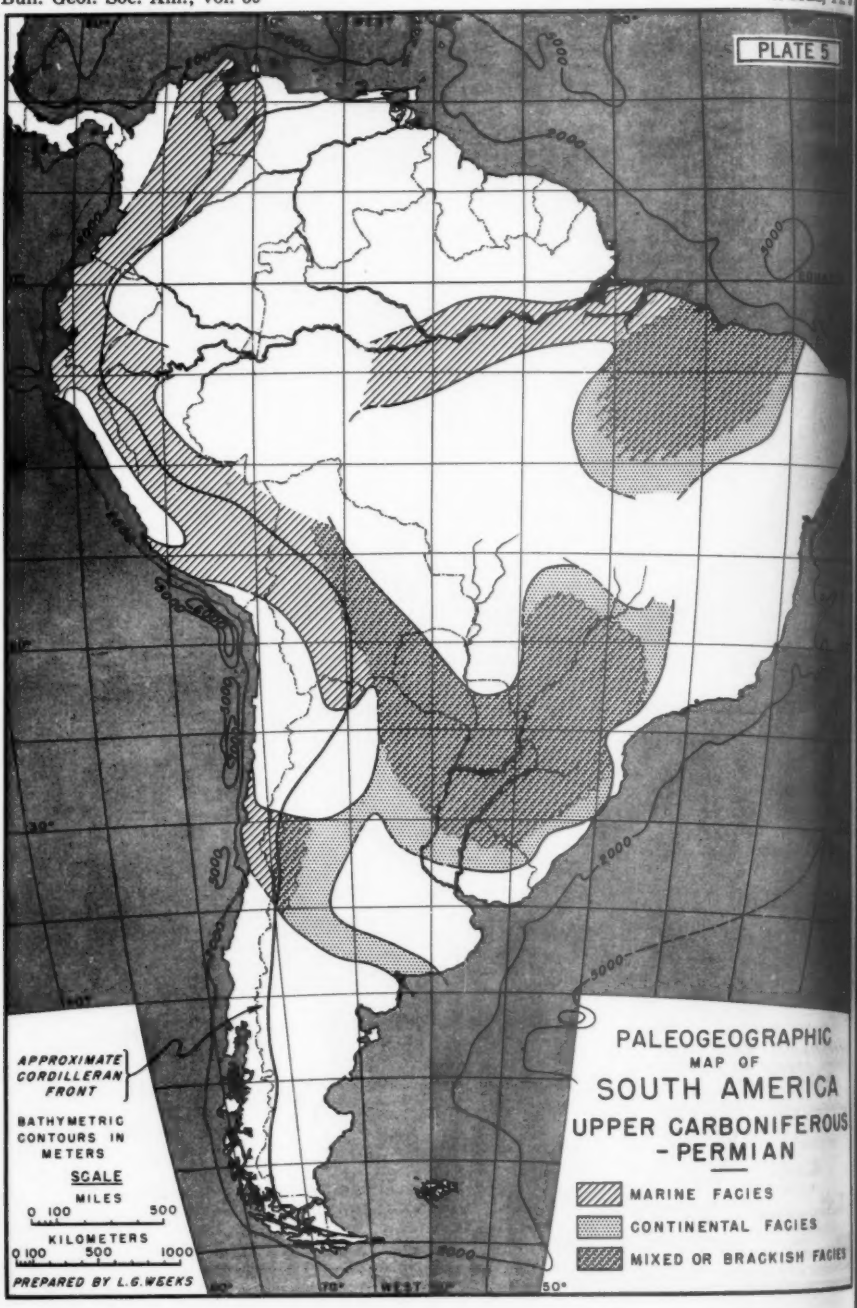


PLATE 5
PALEOGEOGRAPHIC
MAP OF
SOUTH AMERICA
UPPER CARBONIFEROUS
- PERMIAN
MARINE FACIES
CONTINENTAL FACIES
MIXED OR BRACKISH FACIES
APPROXIMATE CORDILLERAN FRONT
BATHYMETRIC CONTOURS IN METERS
SCALE
MILES
0 100 500
KILOMETERS
0 100 500 1000
PREPARED BY L.G. WEEKS
2000
3000
5000
10°
30°
50°
70°
WEST

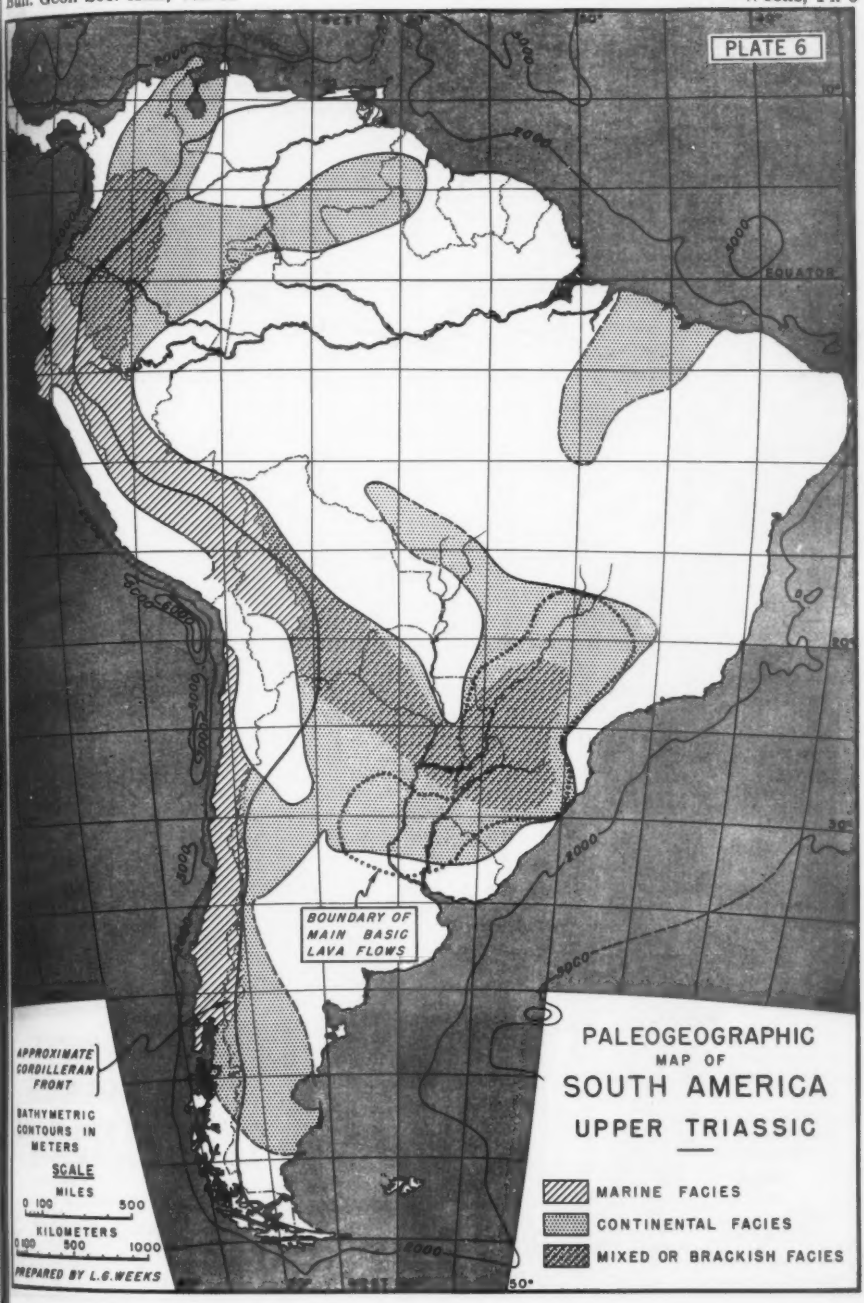


PLATE 6
EQUATOR
BOUNDARY OF MAIN BASIC LAVA FLOWS
APPROXIMATE CORDILLERAN FRONT
BATHYMETRIC CONTOURS IN METERS
SCALE
MILES
0 100 500
KILOMETERS
0 100 500 1000
PREPARED BY L.G.WEEKS
PALEOGEOGRAPHIC MAP OF SOUTH AMERICA
UPPER TRIASSIC
MARINE FACIES
CONTINENTAL FACIES
MIXED OR BRACKISH FACIES

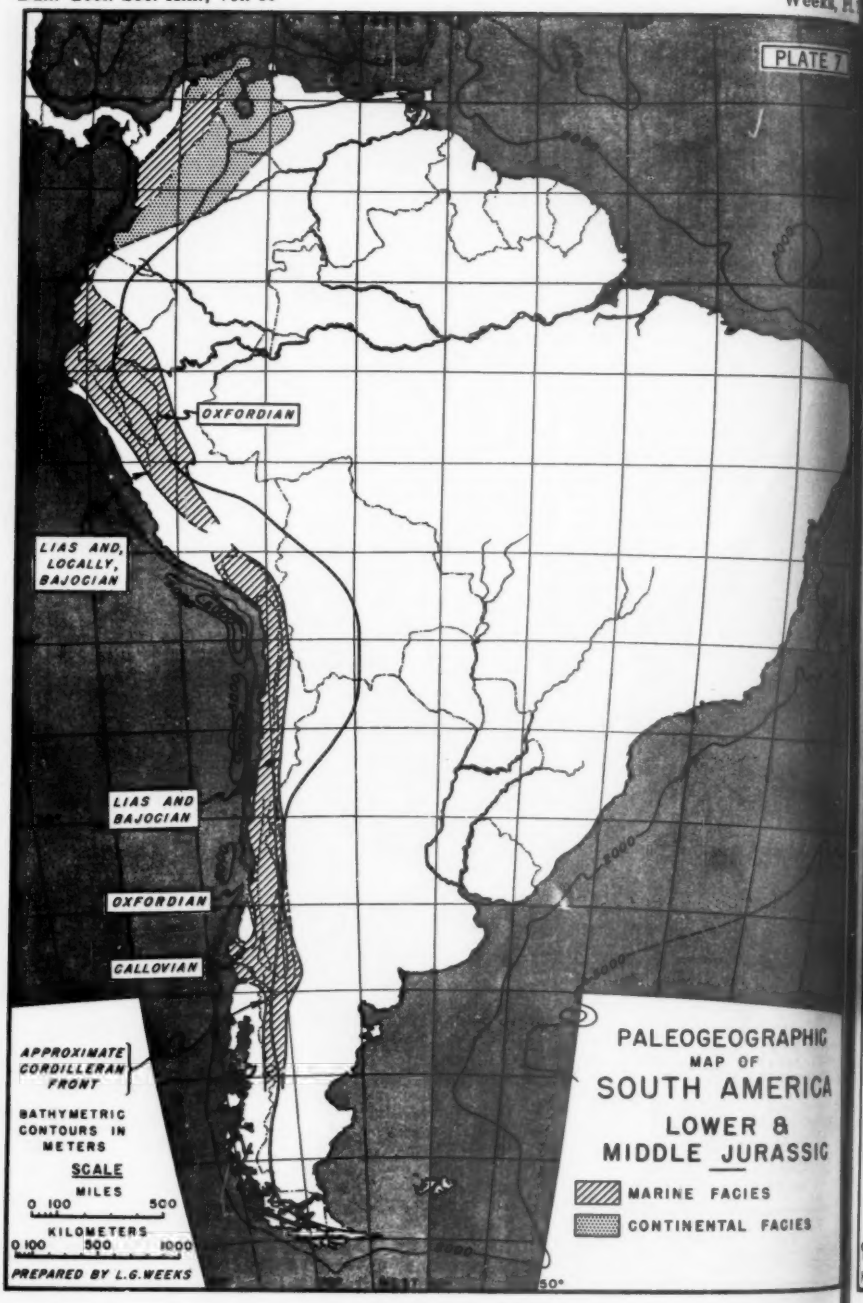


PLATE 7
OXFORDIAN
LIAS AND, LOCALLY, BAJOCIAN
LIAS AND BAJOCIAN
OXFORDIAN
CALLOVIAN
APPROXIMATE CORDILLERAN FRONT
BATHYMETRIC CONTOURS IN METERS
SCALE
MILES
0 100 500
KILOMETERS
0 100 500 1000
PREPARED BY L.G.WEEKS
PALEOGEOGRAPHIC MAP OF
SOUTH AMERICA
LOWER & MIDDLE JURASSIC
MARINE FACIES
CONTINENTAL FACIES
50°

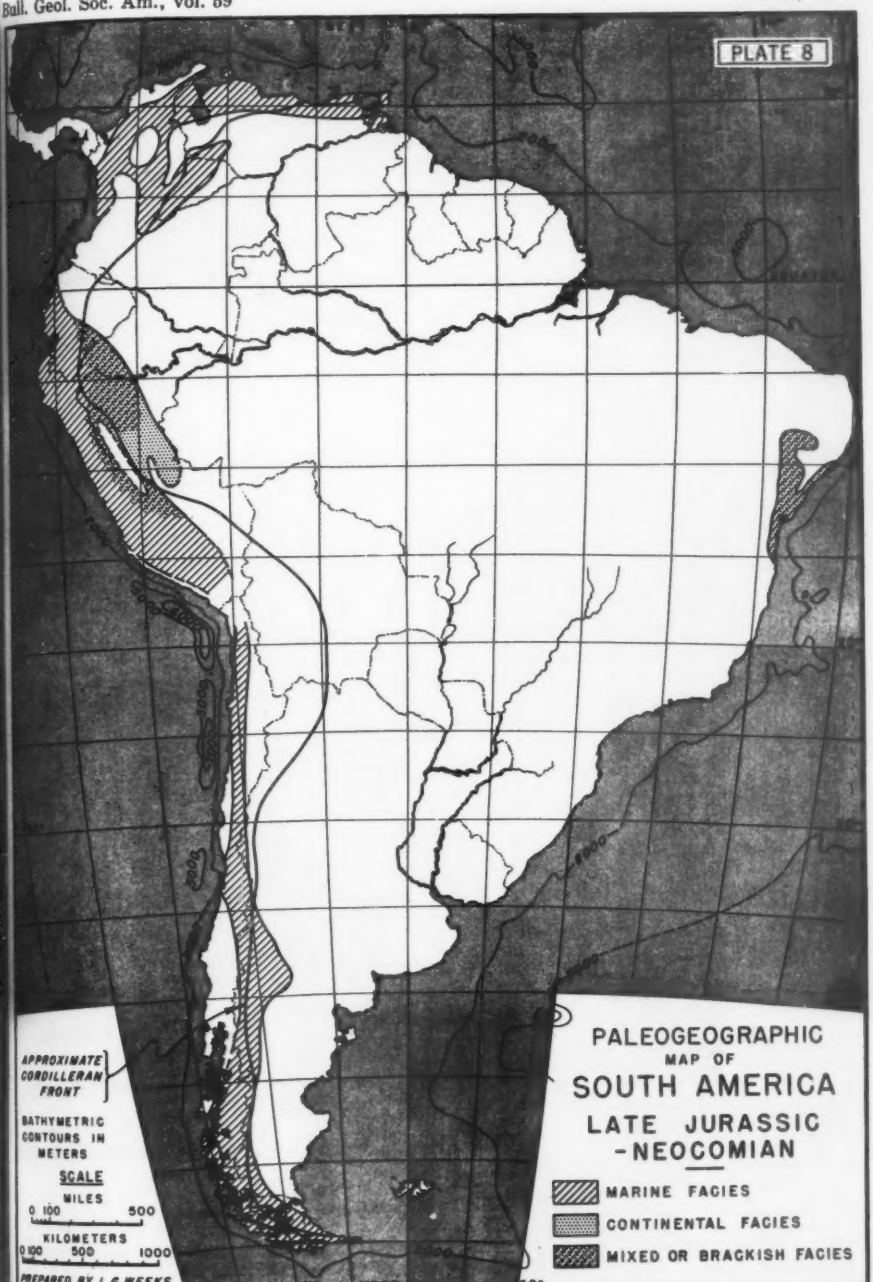


PLATE 8
APPROXIMATE CORDILLERAN FRONT
BATHYMETRIC CONTOURS IN METERS
SCALE
MILES
0 100 500
KILOMETERS
0 100 500 1000
PREPARED BY L.G.WEEKS
PALEOGEOGRAPHIC MAP OF
SOUTH AMERICA
LATE JURASSIC -NEOCOMIAN
MARINE FACIES
CONTINENTAL FACIES
MIXED OR BRACKISH FACIES
30°

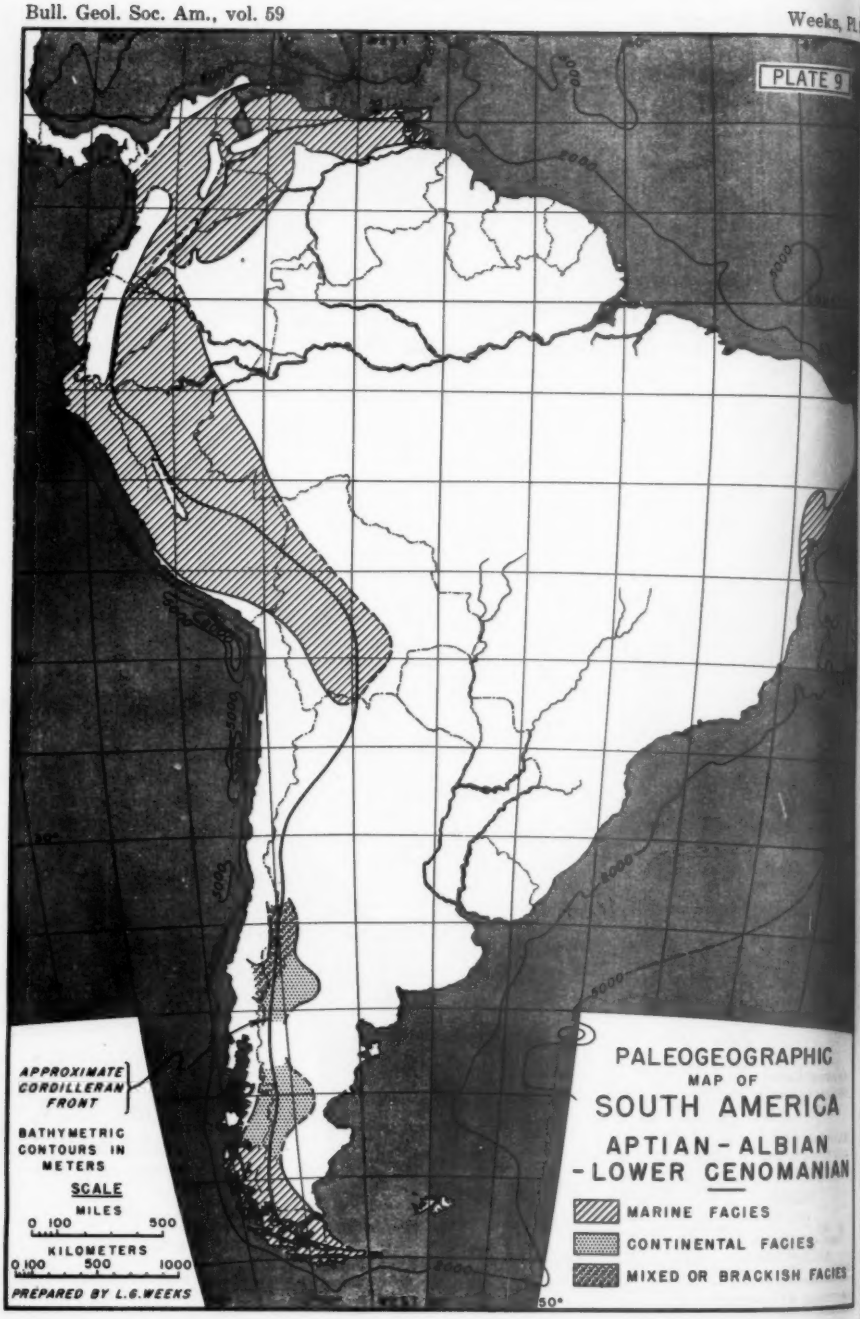


PLATE 9
APPROXIMATE CORDILLERAN FRONT
BATHYMETRIC CONTOURS IN METERS
SCALE
MILES
0 100 500
KILOMETERS
0 100 500 1000
PREPARED BY L.G.WEEKS
PALEOGEOGRAPHIC MAP OF
SOUTH AMERICA
APTIAN - ALBIAN - LOWER CENOMANIAN
MARINE FACIES
CONTINENTAL FACIES
MIXED OR BRACKISH FACIES
2000
3000
5000
50°

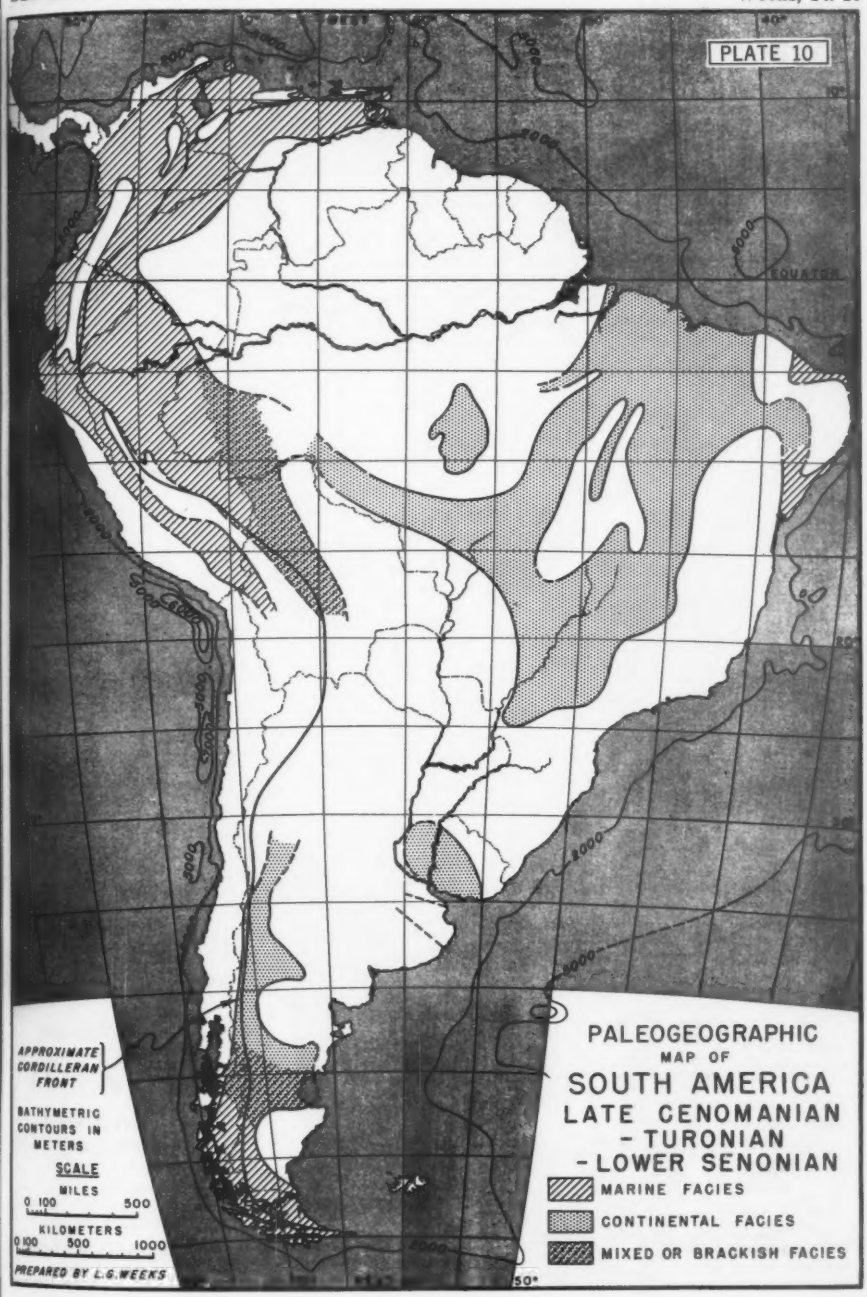


PLATE 10
EQUATOR
APPROXIMATE CORDILLERAN FRONT
BATHYMETRIC CONTOURS IN METERS
SCALE
MILES
0 100 500
KILOMETERS
0 100 500 1000
PREPARED BY L.G. WEEKS
PALEOGEOGRAPHIC MAP OF
SOUTH AMERICA
LATE CENOMANIAN - TURONIAN - LOWER SENONIAN
MARINE FACIES
CONTINENTAL FACIES
MIXED OR BRACKISH FACIES

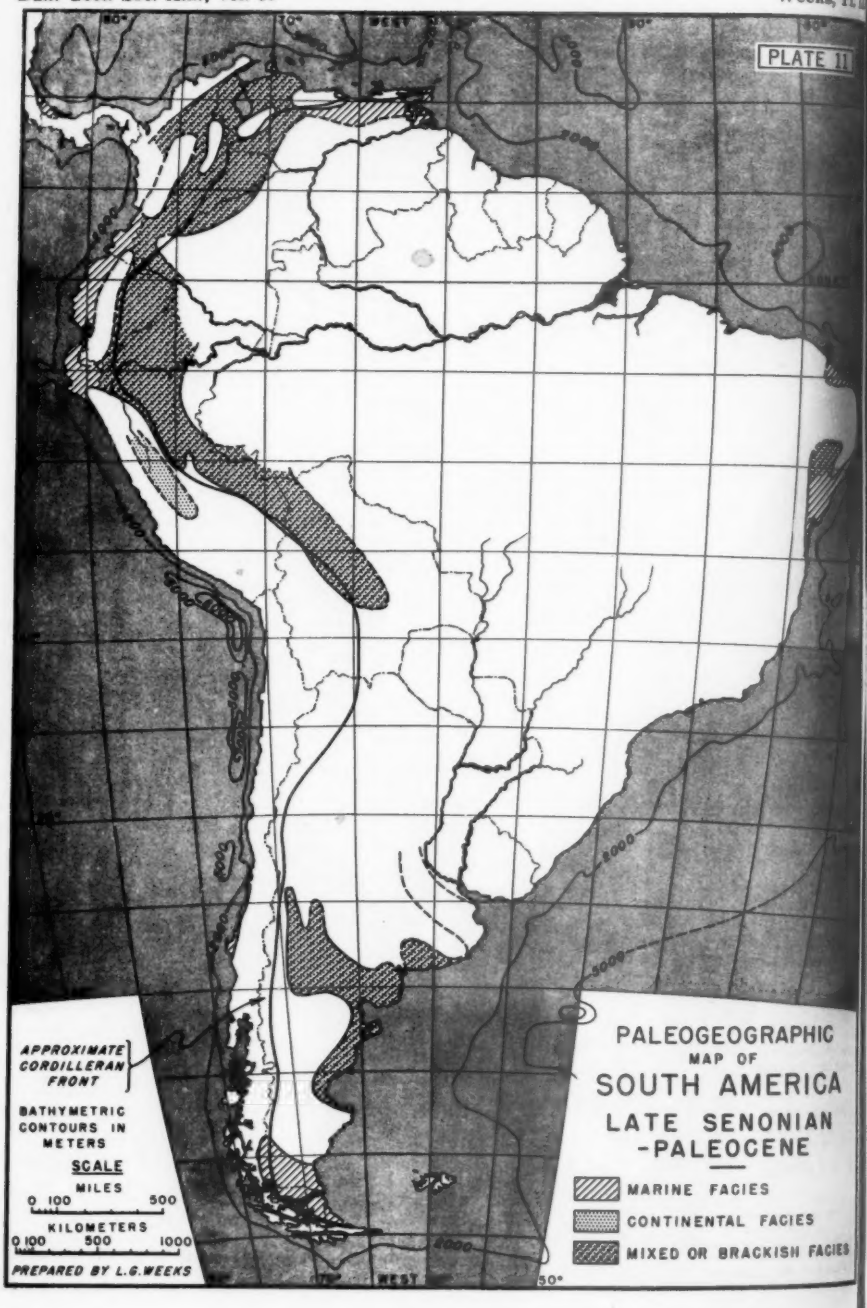


PLATE II
80°
70°
60°
50°
WEST
2000
3000
5000
APPROXIMATE CORDILLERAN FRONT
BATHYMETRIC CONTOURS IN METERS
SCALE
MILES
0 100 500
KILOMETERS
0 100 500 1000
PREPARED BY L.G. WEEKS
PALEOGEOGRAPHIC MAP OF
SOUTH AMERICA
LATE SENONIAN -PALEOCENE
MARINE FACIES
CONTINENTAL FACIES
MIXED OR BRACKISH FACIES

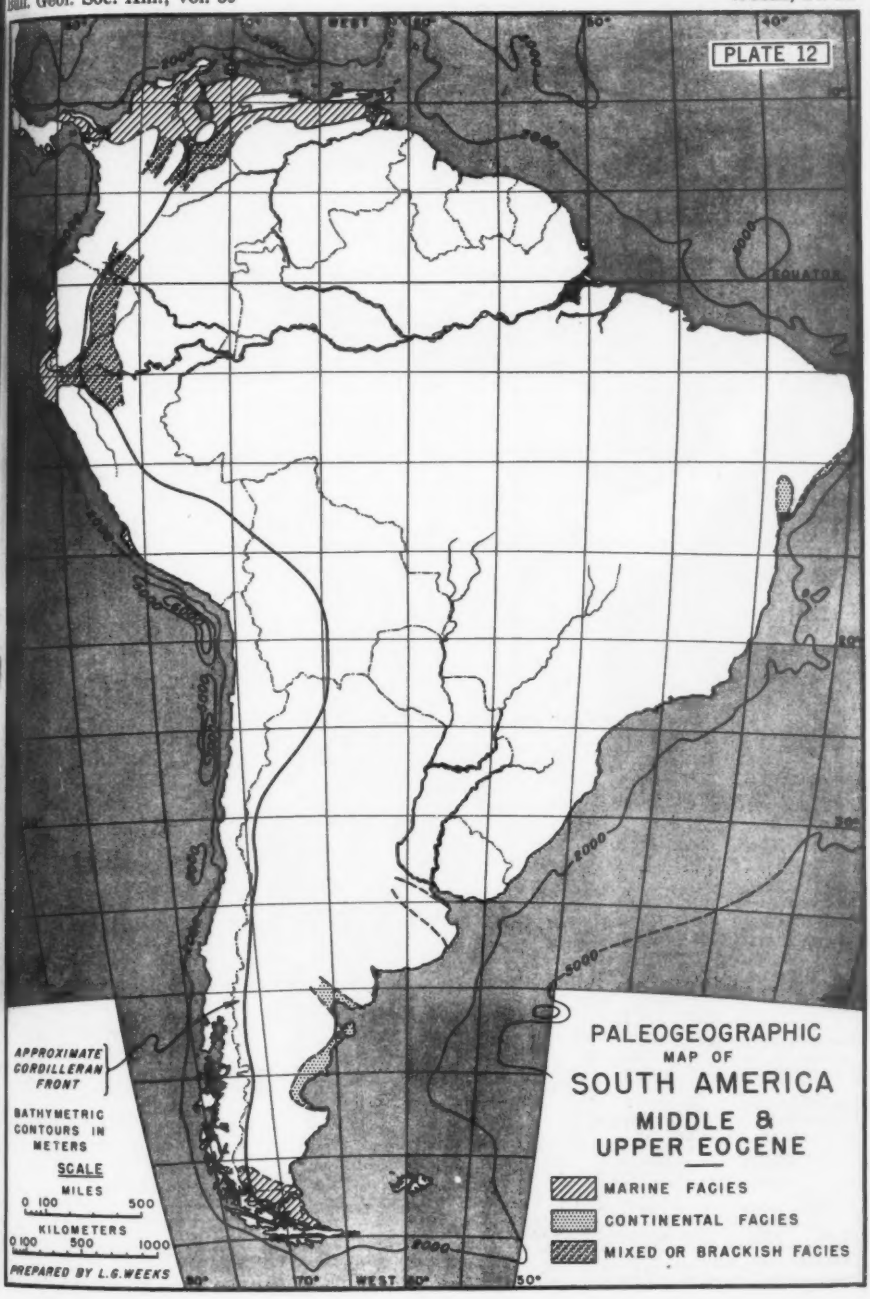


PLATE 12
EQUATOR
APPROXIMATE CORDILLERAN FRONT
BATHYMETRIC CONTOURS IN METERS
SCALE
MILES
0 100 500
KILOMETERS
0 100 500 1000
PREPARED BY L.G.WEEKS
PALEOGEOGRAPHIC MAP OF
SOUTH AMERICA
MIDDLE & UPPER EOCENE
MARINE FACIES
CONTINENTAL FACIES
MIXED OR BRACKISH FACIES

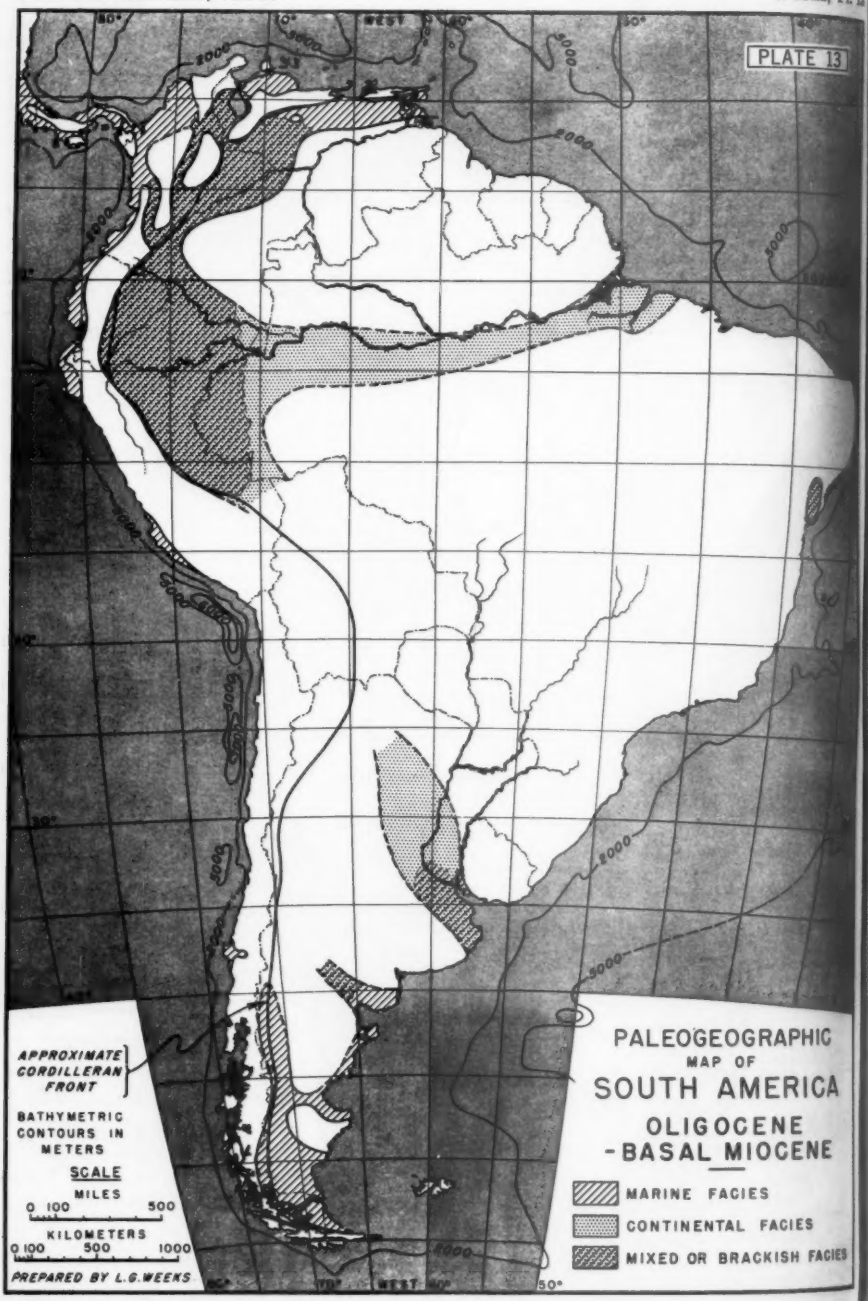


PLATE 13
APPROXIMATE CORDILLERAN FRONT
BATHYMETRIC CONTOURS IN METERS
SCALE
MILES
0 100 500
KILOMETERS
0 100 500 1000
PREPARED BY L.G.WEEKS
PALEOGEOGRAPHIC MAP OF
SOUTH AMERICA
OLIGOCENE - BASAL MIOCENE
MARINE FACIES
CONTINENTAL FACIES
MIXED OR BRACKISH FACIES

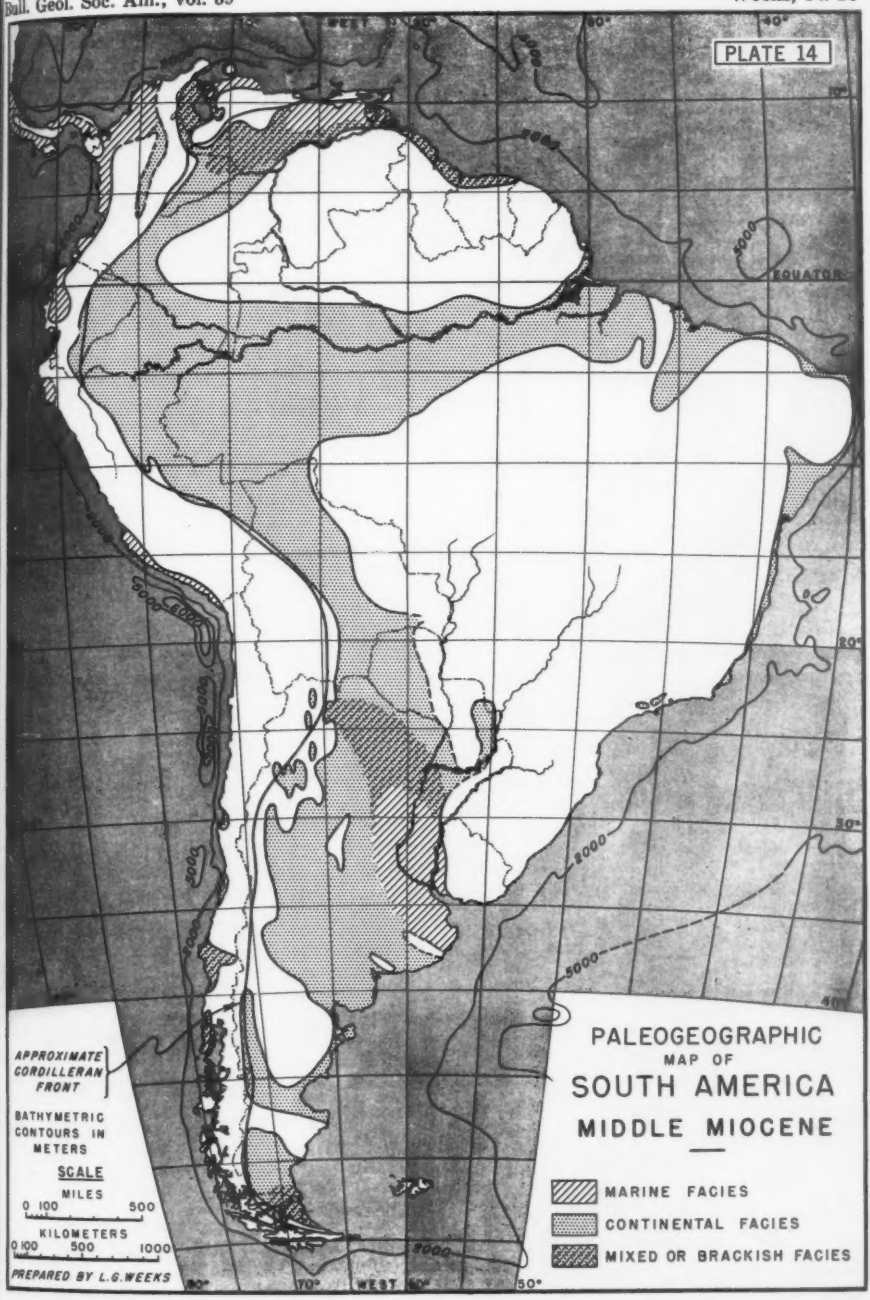


PLATE 14
EQUATOR
APPROXIMATE CORDILLERAN FRONT
BATHYMETRIC CONTOURS IN METERS
SCALE
MILES
0 100 500
KILOMETERS
0 100 500 1000
PREPARED BY L.G.WEEKS
PALEOGEOGRAPHIC MAP OF SOUTH AMERICA
MIDDLE MIOCENE
MARINE FACIES
CONTINENTAL FACIES
MIXED OR BRACKISH FACIES
WEST

PLATE 15
PALEOGEOGRAPHIC
MAP OF
SOUTH AMERICA
UPPER MIOCENE
MARINE FACIES
CONTINENTAL FACIES
MIXED OR BRACKISH FACIES
APPROXIMATE CORDILLERAN FRONT
BATHYMETRIC CONTOURS IN METERS
SCALE
MILES
0 100 500
KILOMETERS
0 100 500 1000
PREPARED BY L.G. WEEKS
EQUATOR
80°
70°
WEST
60°
50°
40°
30°
20°
10°
0°
2000
3000
5000

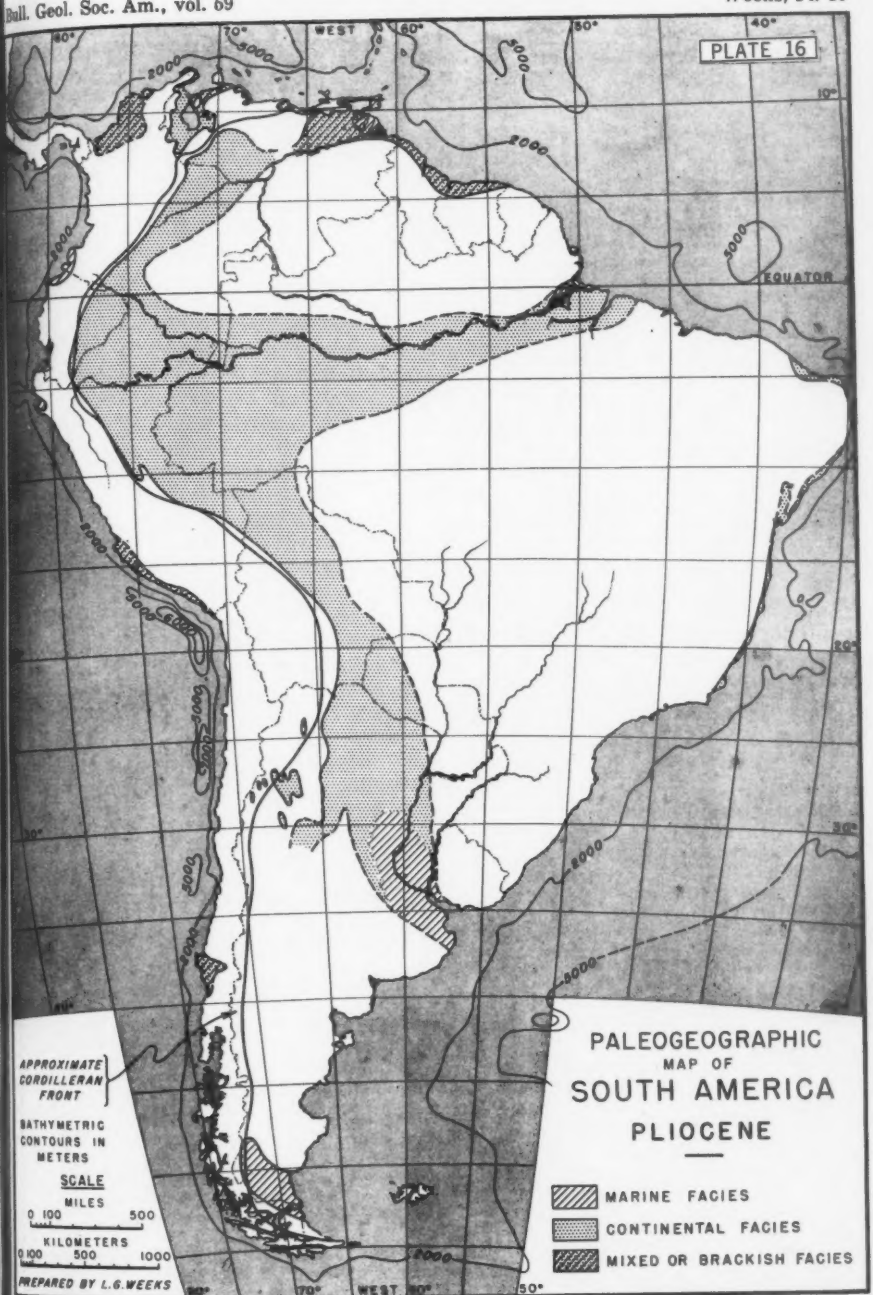


PLATE 16
EQUATOR
APPROXIMATE CORDILLERAN FRONT
BATHYMETRIC CONTOURS IN METERS
SCALE
MILES
0 100 500
KILOMETERS
0 100 500 1000
PREPARED BY L.G.WEEKS
PALEOGEOGRAPHIC MAP OF SOUTH AMERICA PLIOCENE
MARINE FACIES
CONTINENTAL FACIES
MIXED OR BRACKISH FACIES